Journal of Petroleum Science and Engineering 172 (2019) 115–123

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

The discovery and control of slug flow in coalbed methane reservoir

Xianbo Su[a,b,*], Shun Yao[a], Jinxing Song[a], Qian Wang[a], Feng Li[a]

[a] Henan Polytechnic University, Jiaozuo, Henan, 454000, China
[b] Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Jiaozuo, Henan, 454000, China

ARTICLE INFO

Keywords:
Coalbed methane reservoirs
Slug flow
Permeability
Surface tension
Differential pressure

ABSTRACT

Slug flow, which can cause severe velocity sensitivity damage to coalbed methane (CBM) reservoirs, tends to happen at the gas-liquid two-phase flow stage during the CBM production process. However, little attention has been paid to this phenomenon. This paper investigates the factors which can influence the forming of slug flow in CBM reservoirs systematically via a series of laboratory experiments and production data from two CBM wells. Results show that a slug flow is more likely to be formed under the conditions of high reservoir permeability, high fluid surface tension and high producing differential pressure. This is because that both the high permeability and high production differential pressure would lead to a high fluid flow velocity that can cause strong Kelvin-Helmholtz instability effect of the interface wave. Then, the strong Kelvin-Helmholtz instability effect will cause the slug flow. Meanwhile, a high fluid surface tension means that the liquid will form slug flow more easily. The most effective way to restrain slug flow is to utilize a fracturing fluid with low surface tension in combination with continuous, slow and stable productions.

1. Introduction

Gas-liquid two-phase flow is a common phenomenon in oil and gas production, chemical processing, nuclear reactors, geothermal energy, and aerospace industries, and many studies on the gas-liquid two-phase flow have been done since it was initially proposed by Kosterin (1949). A range of factors, e.g. pipeline pressure, gas-liquid phase properties, the shape and the inner-surface properties of the pipeline, and even temperature change, are known to influence gas-liquid two-phase flow properties. The gas-liquid two-phase flow has always been divided into several flow patterns to simplify the study according to its structure and distribution characteristics within a pipeline. Alves (1954) divided the gas-liquid flow patterns into bubble, airmass, stratified, wave, slug, annular, and dispersed forms according to the increasing gas/liquid ratio. During the CBM production, the gas/liquid ratio increases with the dewatering time. Therefore, it is important to study the gas-liquid two-phase flow during CBM production. As a specific flow pattern in the gas-liquid two-phase flow, slug flow can be described as an alternate flow between the liquid slug filling the full pipe cross-section and the big gas bubble (Trapp, 1984). Generally, the Kelvin-Helmholtz instability effect of an interface wave (Kordyban, 1990; Fabre, 2003) has been considered as the basic forming mechanism of a liquid slug. Specifically, as the suction force caused by a pressure change influences the water wave and reaches an amplitude that can overcome the gravity of the water wave, the water wave intensifies. As the interface wave then completely blocks the pipe, a liquid slug forms which are referred to as a slug flow. In an earlier work on the slug flow in square tube sections, Wallis and Dobson (1973) found that gravity exerts a destructive effect on the interface wave, while the aerodynamic lifting force promotes its growth. They also calculated the Kelvin-Helmholtz instability criterion that can be used to predict when a liquid slug will form. Analysis of isolated waves on the laminar interface has also shown that the pressure change on the wave surface is the result of the Bernoulli force and leads to interface wave instability, then a slug will form when a liquid bridge is built between the stratified flow interface and the upper surface of a tube (Taitel and Dukler, 1976, 1977). The interface wave with a maximum growth rate in this paper is called the "most dangerous wave" and is the precondition of the liquid slug forming (Mishima and Ishii, 1980).

CBM production includes many stages, e.g. desorption, diffusion, saturated single-phase flow, unsaturated single-phase flow, gas-water two-phase flow (Su et al., 2017). Under a high reservoir pressure, methane can enter the defect aromatic layer or inter-macromolecules among the coal material, which is called the "crystal diffusion" (Nie et al., 2000; Sun, 2007). Influenced by the concentration gradient, the surface diffusion of methane molecules occurs at the pore surfaces of CBM reservoir when the methane molecular energy is equal to the surface energy (He et al., 2001; Sheng et al., 2014). The Knudsen

* Corresponding author. Henan Polytechnic University, Jiaozuo, Henan, 454000, China.
E-mail address: suxianbo@hpu.edu.cn (X. Su).

https://doi.org/10.1016/j.petrol.2018.09.055
Received 28 March 2018; Received in revised form 12 September 2018; Accepted 18 September 2018
Available online 19 September 2018
0920-4105/ © 2018 Elsevier B.V. All rights reserved.

number, Kn ($Kn = \lambda/d$), can present the ratio of the average free path of the gas molecule, λ, to the pore diameter, d (Knudsen, 1909a; 1909b, 1909c; 1909d). When the Kn is greater than 10, the average free path of the gas molecule is far larger than the pore diameter. Under this condition, the molecules will collide more frequency with the pore surface than with one another, which is known as “Knudsen Diffusion”. When the condition of $1 > Kn > 0.01$ is met, the average free path of the gas molecule will be larger than the pore diameter and the frequency of the collisions between molecules will be higher than those against the pore surfaces, which is called “Fick Diffusion”. However, when the condition that $1 < Kn < 10$ is met, the pore diameter will be slightly smaller than the average free path of gas molecules and the collisions between these molecules and pore surfaces will be just as important as each other. A transition at this point between the “Fick Diffusion” and the “Knudsen Diffusion” tends to occur and is referred to as “Transitional Diffusion” (Mi et al., 2014; Wu et al., 2016). The latter three diffusion types are the main kinds of gas diffusions (Li et al., 2015). After the drainage begins, the water in the fracture is discharged as Darcy flow and leads to a reduction in reservoir pressure, while the methane in the matrix pores desorbs and diffuses into the fractures before it flows into the wellbores as Darcy flow ($Kn < 0.01$). In this process, the CBM flow complies with Darcy's law or the combination of the “Fick Diffusion” and the Darcy flow, which are linear seepages. However, as gas and water pass through a reservoir with fewer cleats, the flow pattern conforms to a low-speed non-linear seepage mode which implies the existence of a threshold pressure gradient. Therefore, as the production continues, the pressure further decreases and some methane desorbs from the matrix and form bubbles in cleats, which were named as unsaturated single-phase flow. As the reservoir pressure decreases further, more gas desorbs and results in gradual increases in gas phase permeability and gas production, while the water production decreases. At this point, the bubbles start to connect to each other until to form a continuous streamline flow that means the start of the gas-water two-phase flow stage.

Recent laboratory research and the analysis of CBM production data show that the slug flow tends to occur during the methane migration and production processes. Firstly, a coal seam fracturing experiment that was carried out in a mine at Jiaozuo, Henan Province, shows that the gas and water gush follow the form of a slug flow. Secondly, when CBM wells subject to nitrogen fracturing or the gas saturation of the reservoirs up to 100%, a slug flow with alternating gas and water productions will occur when the overflow velocity is too high. Thirdly, the data from some CBM production wells where gas and water flows have been automatically recorded reveal that the production of gas and water is uneven and tends to form a slug flow. Additionally, laboratory experiments also show that it is easy to form a strong slug flow at certain pressure differences and under certain permeability conditions during CBM production. The slug flow is characterized by strong intermittence and high drop in pressure, and the intense fluctuations of pressure and instantaneous gas-liquid flow rate in each pipe cross-section. However, the change of liquid flow rate can lead to particle migration and throat plugging within the reservoirs, resulting in a decrease of permeability and velocity-sensitive damage to the reservoirs (Jing et al., 2008; Zhang et al., 2016). In most Chinese CBM wells, coal powder and proponent output are serious (Liu et al., 2014; Chen et al., 2014), which is probably caused by the slug flows. China has experienced more than 30 years of CBM exploration and development, however, only individual blocks have achieved commercial developments. The analysis shows that the existence of the slug flow during the CBM production process might be one of the most important factors that cause the low gas production of CBM wells. This paper presents the results of a slug flow experiment and the CBM production data from a block in central China, and the factors that influence the forming of the slug flow during the CBM production process is systematically evaluated. Finally, a novel method that can be applied to suppress slug flow is proposed.

2. Experimental methods

2.1. Wettability tests

The KCl is commonly used as a clay stabilizer because it can effectively restrain the coal water sensitivity, and is typically applied with a concentration between 1% and 2%. A solution with 1.5% KCl was used in this study as the experimental base liquid, and a kind of surfactant (KO) with the concentration of 0.05% was used to decrease the surface tension of the liquid. The surface tensions of the 1.5% KCl solution and the 1.5% KCl + 0.05% KO solution, as well as their contact angles with the coal samples collected from a block in central China, were tested in this study.

Samples selected from the No. 1 coal seams in the block were crushed into 200 mesh (0.074 mm) for further analysis. A manual compactor was used to compact the pulverized coals to coal tablets with a diameter of 20 mm and thicknesses of about 1 mm at a pressure of 12 MPa.

A JC2000D contact angle measuring instrument with the surface tension measurement ranging from 1×10^{-2} to 2×10^{3} mN m^{-1}, and the pendant drop method were used to test the surface tension by using the 1.5% KCl solution and the 1.5% KCl +0.05% KO solution, respectively. Compacted coal tablets were then placed on a test table under the contact angle measuring instrument and the contact angles were measured.

2.2. Slug flow experiments

2.2.1. Slug flow testing system

A sample tank filled with pulverized coal was used to simulate the CBM reservoir, and helium gas from a high-pressure bottle was used for experiments. A regulator valve was used to control the displacement pressure, and the gas-liquid phase fluid produced from the coal sample chamber was separated by a gas-water separation device so that the two-phase could be separately recorded by gas and liquid flowmeters (Fig. 1).

2.2.2. Coal sample preparation

The permeability of coal consists of two parts of matrix permeability and fracture permeability, and the fracture permeability contributes the most of the effective permeability of coal (Zhang et al., 2006). Concerning that the coal seams generally possess high degrees of heterogeneity, it would be impossible to obtain original coal cores with the same fracture system and permeability. However, it would be conducive to conduct experiments on the coal samples with the same or similar permeability and analyze the impact of other factors on the slug

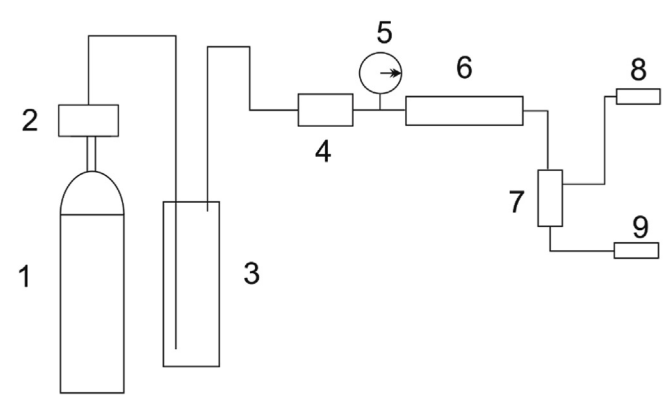

Fig. 1. Schematic of displacement apparatus for slug flow tests. 1-high pressure helium cylinder; 2-constant pressure relief valve; 3-intermediate vessel for humidifying gas; 4-filter; 5-pressure gauge; 6-coal sample chamber; 7-gas-water separator; 8-gas flowmeter; 9- liquid flowmeter.

Download English Version:

https://daneshyari.com/en/article/10156371

Download Persian Version:

https://daneshyari.com/article/10156371

Daneshyari.com