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# A model for gas transport in organic matter with isolated pores in shale gas reservoirs

Yuliang Su[a,**], Han Wang[a,*], Guanglong Sheng[a,b], Wendong Wang[a], Qi Zhang[a], Shiyuan Zhan[a]

[a] School of Petroleum Engineering, China University of Petroleum (East China), No. 66, Changjiang West Road, Huangdao District, Qingdao, 266580, China
[b] Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX, 78713, USA

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ABSTRACT

There are a large number of isolated pores in organic matter (OM) of shale reservoirs, and the isolated pores contain the adsorbed gas and free gas. Experiments showed that when there is a concentration difference between the adsorbed gas on nanopores surface and dissolved gas in OM, gas exchange occurs between the pore surface and OM. The difference of gas concentration among the connected pores, the OM and the isolated pores in the production process leads to the gas transport between the OM and isolated pores, which has a significant impact on shale gas predicted reserves and production.

In this study, we consider the effects of the gas transport and desorption in isolated pores. With the low pressure gradient, the adsorbed gas can desorbs from the pore surface of high pressure regions, and then transport to the low pressure regions and adsorbs on the pore surface in isolated pores. The adsorbed gas can desorb into OM by the concentration difference, and then diffuses as dissolved gas in OM. The apparent permeability model coupled with viscous flow, slip flow, Knudsen diffusion, surface diffusion and gas desorption is adopted in the connected pores and isolated pores. Based on the above understanding, a model that considers the gas transport in the connected pores, the OM and the isolated pores is established. And the effects of the isolated porosity, degrees of isolated pores dispersion and dissolved gas diffusion coefficient are analyzed.

The results shown in this work are strongly affected by the diffusion coefficient of dissolved gas, and when the diffusion coefficient is small, the contribution of the gas production in isolated pores to the cumulative gas production becomes minimal. Hence, with the large diffusion coefficient, when the gas transport is not considered in isolated pores, the existence of isolated pores hinders the diffusion of dissolved gas and result in a significant reduction of cumulative dissolved gas production in OM. And the contribution of the gas in isolated pores gas to the cumulative production cannot be neglected, the cumulative production of shale gas increases with the increase of isolated porosity. The larger the dispersion degree of isolated pores is, the greater the cumulative gas production is. The diffusion coefficient of dissolved gas has a positive effect on the production rate of the gas in isolated pores.

The influence of gas transport in isolated pores on the diffusion of dissolved gas and the seepage law of shale gas reservoirs cannot be neglected.

## 1. Introduction

Shale gas is playing an important role as unconventional gas resources in the word presently whose production is account for 60% of the cumulative production of tight and shale gas reservoirs (Sandoval et al., 2018). Unlike conventional gas resources, shale gas has three storage states that are free gas in both nanopores and natural fractures, adsorbed gas on the surface of nanopores in OM and dissolved gas in OM (Javadpour, 2009; Shabro et al., 2011; Swami, 2012; Wu et al., 2015; Pang et al., 2017; Sheng et al., 2017). The gas content in shale reservoirs is mainly controlled by total organic carbon (TOC) (Liang et al., 2016; Liu et al., 2015; Borjigin et al., 2017; Cao et al., 2017). And shale reservoirs are in a good organic-rich whose TOC is greater than 5% (Ma et al., 2017; Kim et al., 2017). The TOC content has a strong positive influence with the total pore volume and specific surface area (Wang et al., 2017; Guan et al., 2016). And the OM contributes approximately 62% to the total porosity, and the gas in OM pores accounted for about 78% that is a sum of 55% adsorbed gas and 23% free gas (Yang et al., 2016; Sheng et al., 2018). The dissolved gas in OM is also an important part of shale gas production which account for about

* Corresponding author.
** Corresponding author.
*E-mail addresses:* sylupc@gmail.com (Y. Su), wanghan.petro@gmail.com (H. Wang).

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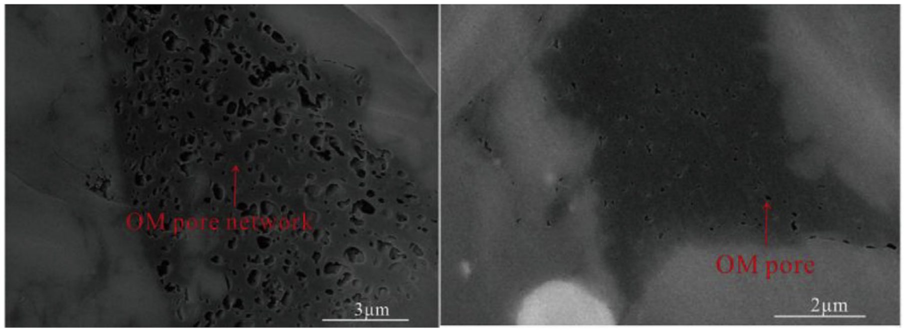
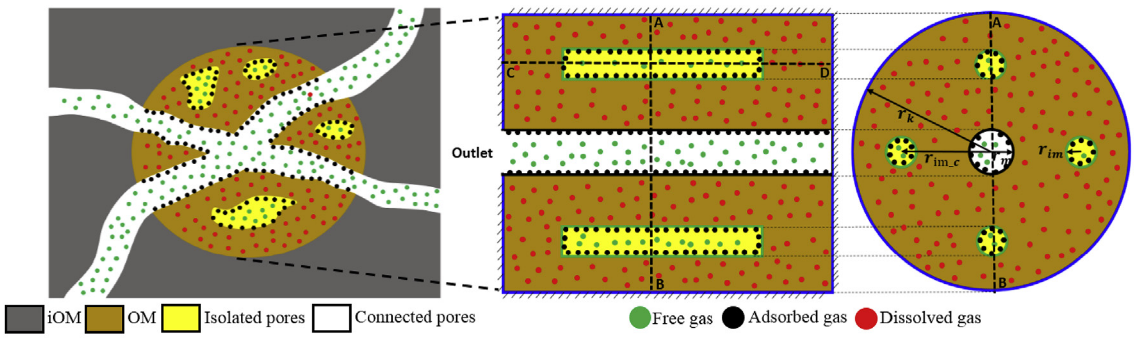



**Fig. 1.** FE-ESEM images of the OM, and OM pores network and isolated pores developed in kerogen. (Shao et al., 2017).




(a) (b)

**Fig. 2.** The structure of shale gas reservoirs. (a). Distribution of the iOM and OM in shale reservoirs. (b). The nanotube-kerogen model of the OM, both connected pores and isolated pores are nanotube that are embedded in the OM (Mi et al., 2014; Huang et al., 2015; Cui et al., 2018).

22% of cumulative production (Etminan et al., 2014). The distribution of OM pores is quite heterogeneous which are composed of better-connected pores and isolated pores (worse connected pores) as shown in Fig. 1(Shao et al., 2017; Li et al., 2016; Wang et al., 2016, 2017). The effective porosity of shale reservoir should be calibrated by connectivity coefficient, because the isolated pores cannot be recognized from the 2D-SEM images (Lu et al., 2017). The coordination number can also reflect the connectivity of OM pores to some extent. The pore with coordination number 0 can be treated as isolated pores and the isolated pores in shale reservoirs account for about 46% of the total pore number from the coordination number. And there is a large amount of the gas in isolated pores due to the large pore volume and specific surface area. The reserves of such shale gas reservoirs cannot be technically practical to be exacted and is overestimated because of the poor connection (Sun et al., 2018). Hence, it is worth investigating whether or not the gas in isolated pores can diffuse into OM.

The gas transport mechanism is complex and diverse which determines gas production from shale gas reservoirs. The gas transport in nanopores is mainly nonlinear flow that is dominated by viscous flow, slip flow, Knudsen diffusion, adsorbed surface diffusion and dissolved gas diffusion (Javadpour et al., 2007; Javadpour, 2009; Xiong et al., 2012; Mi et al., 2014; Sheng et al., 2015; Wu et al., 2016; Yin et al., 2017; Song et al., 2017; Sun et al., 2017). The recognized process of shale gas extraction is that the gas in pores is rapidly produced. With the decrease of pressure in pores, the adsorbed gas on the surface of pores occurs desorption. As the concentration of adsorbed gas decreases, the dissolved gas begin to diffuse onto the surface of pores (Shabro et al., 2012; Huang et al., 2015). With the diffusion of dissolved gas, the gas concentration in OM decreases and there will be a concentration difference between adsorption gas on the surface of isolated pores and dissolved gas in OM. The gas injection experiment of adsorption showed that when the gas was injected into the nanotube, the concentration of adsorbed gas increased because of the increasing of the pressure, so the adsorbed gas began to diffuse into OM to keep the pressure, the concentration and the stress balanced (Cui et al., 2018). Through the slope of the pressure decline obtained from batch pressure decay experiments, the pressure-decline curve shows that the gas transport into the micro- and nano-pores first, and then the gas in pores begins to adsorb onto the inner surface of kerogen pores, and at later time the adsorbed gas diffused into kerogen (Etminan et al., 2014). Therefore, exact for several processes that are accepted for shale gas production, due to the decrease of dissolved gas concentration, there is a concentration difference between the gas in isolated pores and the dissolved gas in OM. In theory, the gas in isolated pores can diffuse into OM. Therefore, it is significant to study gas flow mechanisms in isolated pores and the influencing factors of the gas diffusion between OM and isolated pores.

In this paper, we establish a model that considers connected pores, OM and isolated pores that is based on the representative physical diffusive model of kerogen (Mi et al., 2014). We determine the gas transport mechanisms in isolated pores, and discuss the effects of the isolated porosity, the degree of dispersion and the diffusion coefficient of dissolved gas to the contribution of the gas production from isolated pores to the cumulative production.

## 2. Model construction

As shown in Fig. 2a, a simplified physical model of shale gas reservoir is composed of inorganic matter (iOM) and OM. The connected pores are both in iOM and OM. And there also are some isolated pores in OM. The pores in iOM contain free gas and at the same time the pores in OM are in the presence of adsorbed pores and free gas. There is also some dissolved gas in OM. As shown in Fig. 2b, we make a nanotube-kerogen model which simplify the irregular distribution of connected pores, OM and isolated pores. The white area in the middle of the model indicates the connected pores. The orange area is the OM which is around the connected pores. The yellow area is the isolated pores which are distributed in the OM. The black gas molecules are adsorbed gas,