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Original Article

# Optimization techniques for the secondary development of old gas fields in the Sichuan Basin and their application☆

Xia Chongshuang*, Liu Linqing, Zhang Li, Peng Xian

*Exploration and Development Research Institute, PetroChina Southwest Oil & Gas Field Company, Chengdu, Sichuan 610041, China*

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**Abstract**

After nearly 60 years of development, many old gas fields in the Sichuan Basin have come to middle–late development stages with low pressure and low yield, and some are even on the verge of abandonment, but there are plenty remaining gas resources still undeveloped. Analysis shows that gas fields which have the conditions for the secondary development are faced with many difficulties. For example, it is difficult to produce low permeable reserves and to unset the hydraulic seal which is formed by active formation water. In this paper, therefore, the technical route and selection conditions of old gas fields for the secondary development were comprehensively elaborated with its definition as the beginning. Firstly, geological model forward modeling and production performance inversion characteristic curve diagnosis are performed by using the pressure normalization curve and the identification and quantitative description method for multiple sets of storage–seepage body of complex karst fracture–cavity systems is put forward, after the multiple storage–seepage body mode of fracture–cavity systems is established. Combined with the new occurrence mode of gas and water in U-shape pipes, a new calculation technology for natural gas reserves of multiple fracture–cavity systems with strong water invasion is developed. Secondly, a numerical model of pore–cavity–fracture triple media is built, and simulation and result evaluation technology for the production pattern of "drainage by horizontal wells + gas production by vertical wells" in bottom-water fracture and cavity gas reservoirs with strong water invasion is developed. Thirdly, the geological model of gas reservoirs is reconstructed with the support of the integration technologies which are formed based on fine gas reservoir description. Low permeable reserves of gas reservoirs are evaluated based on each classification. The effective producing ratio is increased further by using the technologies of well pattern optimization, horizontal-well geosteering and staged acid fracturing. And fourthly, overall simulation, optimization and prediction technology for regional pipeline net-works is developed by building a multi-node multi-link gas transmission pipeline network model. Application shows that this technology plays an important role in productivity construction, recovery factor improvement, production decline delay and production stabilization of old gas fields.



*Keywords:* Sichuan Basin; Old gas field; Secondary development; Active water invasion; Multiple sets of storage–seepage body; Drainage system; Well pattern; Pipe network; Low permeable reserves producing; Recovery factor

After 60 years of development, prominent difficulties and challenges are frequently encountered in old gas fields in the Sichuan Basin. First, formation water is produced and water invasion is active. The production declines more quickly and the recovery factor decreases greatly. Second, hydraulic sealed gas is formed as a result of active water invasion, and so it is difficult to improve the recovery factor of gas reservoirs. Third, the widely distributed low-permeable reserves have a low gas production rate and producing percent. Fourth, gas wells reveal low production pressure and rate, so the conventional recovery method is no longer workable due to a high

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* Corresponding author.
*E-mail address:* xiachongshuang@petrochina.com.cn (Xia CS.).

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water–gas ratio. And fifth, the production management is challenging, since there are many supporting facilities and complicated gathering & transmission systems in old gas fields, and some pipelines have suffered serious corrosion after long-term operation.

Most of the above old gas fields are currently at middle–late development stages and some old gas fields contain a large quantity of remaining reserves that cannot be produced effectively. Affected by active formation water, some gas wells have water produced or are flooded, making a lot of gas in place hydraulically sealed. Such gas reservoirs are impossibly recovered by conventional methods and on the verge of abandonment. Especially, a number of widely distributed low-permeable gas reservoirs cannot be efficiently recovered with the existing gas reservoir engineering technologies, recovery methods and process techniques in order to offset the quick decline of productivity. Those complex gas reservoirs with active water invasion and those with low permeability have the conditions for secondary development, but their recovery factors cannot be further improved by using such adjustment measures based on available geologic knowledge of gas reservoirs, conventional gas recovery by water drainage technology, stimulation technology and producing well pattern. Therefore, it is necessary to carry out technological research on secondary development for those gas reservoirs, so as to effectively utilize the valuable proven natural gas resources.

The following technical difficulties may exist in the secondary development.

1) The gas reservoir in Maokou Fm of Lower Permian in the South Sichuan Basin is a complex fracture–cavity reservoir with active water invasion [1–3]. In its early stage, due to the limitations in drilling technologies, drilling was finished when a large quantity of leakage of drilling fluid and malignant blowout occurred. As a result, only inadequate data of well logging, mud logging and coring were acquired; most of the seismic data were dominated by 2D digital seismic data, and 3D digital seismic data were old with less line folds. In the secondary development of complex water-bearing fracture–cavity gas reservoirs, it is challenging to understand the geological model of the fracture–cavity reservoirs, and establish the identification and quantitative evaluation technology for multiple storage–seepage bodies in complex karst water-bearing fracture–cavity system to identify and quantitatively evaluate the multiple storage–seepage bodies in complex karst water-bearing fracture–cavity systems and figure out the remaining reserves.
2) In the fracture–cavity type gas reservoirs with active bottom water in the Sichuan Basin, such as Weiyuan Sinian gas reservoir, the formation water invasion is strong with vertical breakthrough and lateral invasion. The production stops due to the complete water flooding. The remaining measured gas initially in place is $255.14 \times 10^8$ $m^3$ and the recovery percent is only 36.22%. The single media system is not sufficient to deepen the understanding of seepage mechanism of the gas reservoir. In the secondary development of the gas reservoir, it is technically challenging to quantitatively calculate the distribution of remaining reserves after water flooding, simulate the seepage mechanism of fracture–cavity type bottom-water gas reservoirs with strong water invasion by using the multiple media system to find out the distribution of hydraulically-sealed reserves, and use new drainage well patterns to improve the producing ratio of hydraulically-sealed reserves.
3) In the carbonate low-permeability gas reservoirs of the Sichuan Basin, the producing effect of the low-permeable reserves via vertical wells is not satisfactory and the production of reserves in the low-permeable area via gas wells in the adjacent high-permeability zones is not clear. In carrying out the secondary development for improving the producing percent of low-permeable reserves, it is challenging to make clear the producing status of the carbonate low-permeability gas reservoirs and the remaining reserves distribution, evaluate the producing potential of the low permeable reserves, and propose suitable and supporting development technologies.
4) In old gas fields, surface equipment runs at a low load and high energy consumption per unit. To address these problems, it is essential to optimize the ground system operation and simplify the gathering and transmission process to realize energy saving and consumption reduction.

## 1. Selection of old gas fields for secondary development

The secondary development of gas fields is a systematic strategy for old gas fields with a huge resource potential. To be specific, for such old gas fields that are producing at a low rate and low efficiency or will be abandoned under the existing development conditions, a new development system is reconstructed based on the latest practical technology and according to the brand-new idea and the technical solution of "reconstructing the subsurface recognition systems, rebuilding the well patterns and reorganizing the surface processes". In this way, the ultimate recovery factor of the gas fields is enhanced, and the safe, environmental protective, energy saving and high efficient development is finally realized.

According to the development potential analysis, the old gas fields that meet one of the following conditions may be given the priority for secondary development, provided that the recovery factor can be enhanced by above 10%.

1) The recovery percent of recoverable reserves is higher than 70%, and the latest calibrated recovery factor is less than 70% for water-free gas reservoirs and less than 50% for water-bearing gas reservoirs.
2) The gas fields can no longer be normally developed due to low wellhead pressure, water flooding and other factors.