

Study on Optimization of Drainage Gas Recovery Program Based on DEA Model

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Abstract. In this paper, the data about drainage gas recovery in 11 middle-shallow layer of gas fields in western Sichuan gas field are studied, and the alternative drainage gas recovery program is selected. According to the geological characteristics, the water production mechanism of gas reservoirs and the water production characteristics of water-yielding gas well, the technological economic integrated evaluation indicators of the middle-shallow layer reservoirs in western Sichuan are established. By establishing the optimization model of DEA drainage gas recovery program, the technological program is analyzed, and the economic benefit is accurately evaluated, so as to select the optimal drainage gas recovery program.

Introduction

Most of the gas fields in western Sichuan have entered the middle and late stages of development and most of them are in the low-pressure and low-yielding phase, in particular, the 11 middle-shallow layer gas fields or blocks of Xinchang, Luodai, Majing, Xindu are typical representatives. Most of these gas fields are now relying on foam scrubbing, vehicle-mounted air lift, centralized pressurization, single point skid supercharger, speed string, capillary bubble row, plunger gas lift, vortex tube, tanker gas lift and other drainage gas recovery measures to maintain the normal production of gas wells, the increased unit caused by such measures has accounted for about 5% of total output. In views of the wellhead pressure and production distribution in western Sichuan gas field, gas wells with the wellhead oil pressure of less than 1MPa account for 30%; gas wells with the wellhead oil pressure between 1.0-2.0MPa account for 39.4%; gas wells with wellhead oil pressure between 2.0-2.5MPa account for 8.6 %. There are a total of 288 gas wells that have the daily gas production of less than 0.5×10⁴m³, and have the annual output of 2.1971×10⁸m³, accounting for 19.64% of total annual output. In addition, there are a total of 250 gas wells that have the output of less than 0.5×10⁴m³, the wellhead pressure of less than 2.5MPa, and the annual production output of 1.8×10⁸m³, accounting for 16.1% of total annual output. From these data it can be seen that, low-pressure low-yield gas wells have occupied a considerable proportion. However, as some gas wells can’t reach the carrying conditions, so the pressure boost measures must be taken to improve the output of gas wells. Therefore, targeted at the difficulties encountered among the current low-pressure and low-output gas wells, the technologies of discharge, plunger gas lift and foam drainage are studied. The optimal gas recovery program is selected, so that low-pressure low-output gas wells can conduct normal production and improve the output of single well, which has a pivotal role for the stable yield in western Sichuan gas field.

Process Technologies about Drainage Gas Recovery Technology in Domestic and Abroad

The United States and the former Soviet Union proposed process technologies about drainage gas recovery in 1950s, and used them in the production, of which, foam drainage process was mostly widely applied. In recent years, the United States has achieved a breakthrough in the small tube gas
lift, plunger gas lift and foam drainage, these technologies are also been used in the production, and the gas output of wells has been greatly improved accordingly [1]. With the in-depth studies on the efficient and low-cost drainage gas recovery processes, more and more technologies are being used in process optimization and transformation [2]. Multi-disciplinary gas pool water control technology that combines single well drainage technology and gas pool engineering is considered as a typical [3], and a variety of advanced drainage gas recovery programs area also formed [4]. In China, the study on gas recovery technology started from 1978, after decades of research, a variety of supporting gas recovery processes have been developed, such as bubble row, concentrated pressurization and so on [5]. At present, various gas recovery programs are widely used in production. However, due to the specific situation of various gas wells, it is necessary to improve the internal air pressure and improve the output of gas wells through different methods.

Optimization of Drainage Gas Recovery Programs

The implementation feasibility of drainage gas recovery process is the first consideration when selecting the programs, such as the geological factors, mining factors and environmental factors to be taken into account to increase the efficiency and longevity of the drainage gas recovery equipment; besides, mining-related conditions, operating environment of well site, power supply, and the quality of management personnel also need to be considered. The primary consideration of selecting the drainage gas recovery technology is the economic benefits, and the most cost-effective one will be picked out through comprehensive comparison [6]. Therefore, the factors to be considered can be divided into technical and economic two categories [7]. Generally speaking, technical factors and economic factors need to be considered comprehensively, in order to measure and evaluate the entire program by establishing a set of index system. The index system should have interpretation, evaluation and early warning functions. During the process of establishing index system, not only the logical classification of index needs to considered, but also the combination of index needs to be taken into account. For an evaluation worker, the evaluation index system is a prerequisite for the evaluation work, if you need to evaluate a target or related program, a certain evaluation system is needed to be used as the premise [8]. Therefore, the evaluation system must be subordinate to a certain target system, and play a guiding role in the evaluation activities, only in this way, the results of the selection program is effective.

Based on the investigation of the drainage gas recovery technologies in western Sichuan gas field, its influencing factors are analyzed from the technical and economic perspectives. Finally, 10 indicators are selected to carry out comprehensive technical and economic evaluation on drainage gas recovery technologies in western Sichuan gas field.

Selection of Technical Indicators and Parameters

Technical factors used in the comprehensive evaluation of drainage gas recovery include: increased gas productivity, water yield, casing pressure-oil pressure, adaptability of mining conditions, technical performance of gas recovery equipment, drainage volume and gas output as well as the maximum well depth, etc. The following Table 1 is obtained after analyzing the influencing factors of the drainage gas recovery technologies and the index data under the process program.

Table 1. Technical Parameters of the Programs.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Increased Gas Productivity (10^4m³/d)</th>
<th>Water Yield (m³/d)</th>
<th>Casing Pressure-Oil Pressure (MPa)</th>
<th>adaptability of mining conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program1 Foam Scrubbing</td>
<td>0.5561</td>
<td>26.872</td>
<td>0.554</td>
<td>260</td>
</tr>
<tr>
<td>Program2 Capillary Bubble Row</td>
<td>0.1996</td>
<td>31.920</td>
<td>3.295</td>
<td>120</td>
</tr>
<tr>
<td>Program3 Vehicle-Mounted Air Lift</td>
<td>0.3482</td>
<td>30.293</td>
<td>3.040</td>
<td>260</td>
</tr>
<tr>
<td>Program4 Coiled Tubing</td>
<td>0.1576</td>
<td>33.262</td>
<td>3.120</td>
<td>130</td>
</tr>
<tr>
<td>Program5 Work-over Rig Pumping</td>
<td>2.1417</td>
<td>27.354</td>
<td>2.890</td>
<td>190</td>
</tr>
<tr>
<td>Program6 Centralized Pressurization</td>
<td>0.4293</td>
<td>28.912</td>
<td>0.700</td>
<td>210</td>
</tr>
<tr>
<td>Program7 Vortex Tube</td>
<td>0.0504</td>
<td>34.268</td>
<td>1.100</td>
<td>110</td>
</tr>
</tbody>
</table>
Selection of Economic Indicators and Parameters

Through the expert opinion and industry experience, the investment recovery period, the financial net present value rate, the internal rate of return, the capacity utilization rate at balance point, investment profitability and cost income ratio six financial indicators are selected. The economic indicators of the above-mentioned process program are sorted out to prepare financial form, so as to get the index value of each program, see Table 2 below.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment Recovery Period</th>
<th>Financial Net Present Value Rate</th>
<th>Internal Rate of Return</th>
<th>Capacity Utilization Rate at Balance Point</th>
<th>Investment Profitability</th>
<th>Cost Income Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program1 Foam Scrubbing</td>
<td>8.2865</td>
<td>0.2869</td>
<td>0.6637</td>
<td>0.0831</td>
<td>0.2983</td>
<td>0.1302</td>
</tr>
<tr>
<td>Program2 Capillary Bubble Row</td>
<td>10.4140</td>
<td>0.2300</td>
<td>0.2264</td>
<td>0.1879</td>
<td>0.2099</td>
<td>0.1726</td>
</tr>
<tr>
<td>Program3 Vehicle-Mounted Air Lift</td>
<td>9.0278</td>
<td>0.2567</td>
<td>0.5965</td>
<td>0.0395</td>
<td>0.2190</td>
<td>0.1659</td>
</tr>
<tr>
<td>Program4 Coiled Tubing</td>
<td>10.6567</td>
<td>-0.1676</td>
<td>0.0698</td>
<td>0.7051</td>
<td>0.2017</td>
<td>0.1787</td>
</tr>
<tr>
<td>Program5 Work-over Rig Pumping</td>
<td>8.7036</td>
<td>0.1916</td>
<td>0.4829</td>
<td>0.1568</td>
<td>0.2416</td>
<td>0.1465</td>
</tr>
<tr>
<td>Program6 Centralized Pressurization</td>
<td>9.0825</td>
<td>0.1613</td>
<td>0.3747</td>
<td>0.6223</td>
<td>0.1956</td>
<td>0.1688</td>
</tr>
<tr>
<td>Program7 Vortex Tube</td>
<td>9.5442</td>
<td>0.1381</td>
<td>0.1189</td>
<td>0.3877</td>
<td>0.1922</td>
<td>0.1735</td>
</tr>
</tbody>
</table>

Data Preprocessing

The data is standardized by the preprocessing method, and then the normalized data is obtained. The data are shown in Table 3.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Program 1</th>
<th>Program 2</th>
<th>Program 3</th>
<th>Program 4</th>
<th>Program 5</th>
<th>Program 6</th>
<th>Program 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased Gas Productivity</td>
<td>0.5561</td>
<td>0.1996</td>
<td>0.3482</td>
<td>0.1576</td>
<td>2.1417</td>
<td>0.4293</td>
<td>0.5040</td>
</tr>
<tr>
<td>Water Yield</td>
<td>1.0000</td>
<td>0.3175</td>
<td>0.5375</td>
<td>0.1360</td>
<td>0.9348</td>
<td>0.7242</td>
<td>0</td>
</tr>
<tr>
<td>Casing Pressure-Oil Pressure</td>
<td>0.5540</td>
<td>3.2950</td>
<td>3.0400</td>
<td>3.1200</td>
<td>2.8900</td>
<td>0.7000</td>
<td>1.1000</td>
</tr>
<tr>
<td>Mining Geological Condition</td>
<td>1.0000</td>
<td>0.4615</td>
<td>1.0000</td>
<td>0.5000</td>
<td>0.7308</td>
<td>0.8077</td>
<td>0.4231</td>
</tr>
<tr>
<td>Income Contingent</td>
<td>1.0000</td>
<td>0.1258</td>
<td>0.2639</td>
<td>0</td>
<td>0.6639</td>
<td>0.2041</td>
<td>0.1072</td>
</tr>
<tr>
<td>Investment Profit Rate</td>
<td>1.0000</td>
<td>0.1024</td>
<td>0.6872</td>
<td>0</td>
<td>0.8240</td>
<td>0.6642</td>
<td>0.4694</td>
</tr>
<tr>
<td>Financial Net Present Value Ratio</td>
<td>0.2869</td>
<td>0.2300</td>
<td>0.2567</td>
<td>-0.1676</td>
<td>0.1916</td>
<td>0.1613</td>
<td>0.1381</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>0.6637</td>
<td>0.2264</td>
<td>0.6965</td>
<td>0.0698</td>
<td>0.4829</td>
<td>0.3747</td>
<td>0.1189</td>
</tr>
<tr>
<td>Capacity Utilization</td>
<td>0.9345</td>
<td>0.7770</td>
<td>1.0000</td>
<td>0</td>
<td>0.8238</td>
<td>0.1244</td>
<td>0.4769</td>
</tr>
<tr>
<td>Investment Recovery Period</td>
<td>0.2983</td>
<td>0.2099</td>
<td>0.2190</td>
<td>0.2017</td>
<td>0.2416</td>
<td>0.1956</td>
<td>0.1922</td>
</tr>
</tbody>
</table>

Optimization of Drainage Gas Recovery Program Based on DEA Model

Data Envelopment Analysis (DEA) is a quantitative analysis method for the effectiveness evaluation at the same level of decision-making units with multi-input and multi-output\(^{[10]}\). The drainage gas recovery program used in western Sichuan gas wells to boost pressure belongs to a multi-input and multi-output system, and you can use DEA to evaluate the effectiveness of production. In the DEA model, the DMU method is mostly widely used. The DMU model must have the following three characteristics, namely, the same objectives and tasks, the same external environment, the same input indicators and output indicators:

Suppose there are \( n \) decision units \( DMU_j, (j = 1, 2, \ldots, n) \), where each decision unit has \( m \) inputs and \( s \) kinds of outputs, thus forming a multi-index input and multi-index output evaluation system contains \( n \) decision units, and each decision-making unit represents different economic indicators, as shown in Figure 1.
In the evaluation system, $x_{ij} = DMU_j$ represents the $i^{th}$ input, and $y_{ij} = DMU_j$ represents the $i^{th}$ output and $u_i$ is a measure of the $i^{th}$ input; and $v_r$ is a measure of the $r^{th}$ output; As $X_i$ and $Y_j$ represent the input and output vectors of $DMU_j$, respectively, and $j = 1, 2, ..., n$ are all known data; since these data can be obtained from the current data; therefore, $v$ and $u$ can be treated as output weight vectors of $m$ input and $s$ output.

$$h_j = \sum_{r=1}^{s} \frac{v_r y_{rj}}{\sum_{i=1}^{m} u_i x_{ij}}$$

The weight vector for the $j_0$ input and output is expressed as:

$$x_{0} = (x_{1j_0}, x_{2j_0}, \cdots, x_{mj_0})$$

$$y_{0} = (y_{1j_0}, y_{2j_0}, \cdots, y_{nj_0})$$

$h_{j_0}$ is the efficiency index value calculated for the $j^{th}$ decision unit. From $h_{j_0}$ value point of view, by adjusting $u$, $v$ to realize $h_j \leq 1$ $(j = 1, 2, ..., n)$, so that the value of $h_{j_0}$ can be maximized, thus constructing the optimal model. Therefore, as long as certain constraints are met, the requirements can also be met by selecting a best weight coefficient $u$ and $v$.

$$T = \{(x, y) | \sum_{j=1}^{n} \lambda_j x_j \leq x, \sum_{j=1}^{n} \lambda_j y_j \geq y, \lambda_j \geq 0, j = 1, 2, \cdots, n\}$$

$$(x_j, y_j) \in T, (j = 1, 2, \cdots, n)$$
This model is called $C^2R$ model, where $T$ represents the production possibility set, which means that if there are $n$ decision units, they are comparable to each other, and each decision unit has a set of input index values and output index for expression. In the evaluation unit $DMU_j$, the input index value $x_j$ and the output index value $y_j$ can be expressed as:

$$x_j = (x_{1j}, x_{2j}, \ldots, x_{nj})^T$$  \hspace{1cm} (6)

$$y_j = (y_{1j}, y_{2j}, \ldots, y_{nj})^T$$  \hspace{1cm} (7)

The set $t = \{(x, y) \text{ output } y \text{ can be produced with input } x\}$ is the production possibility set, which is the composition of all possible production activities.

The DEA model evaluation method proposed in this paper is an improved DEA method, which realizes the full evaluation and sequencing of the efficiency of all decision-making units. The concrete idea is as follows:

For other evaluation units, $C^2R$ model can be used to evaluate the relative validity of the $j$th evaluation unit; this method can also be referred to as the DEA model for evaluating the relative validity. When $C^2R$ model is used for evaluation, it is often found that multiple decision-making units are relatively effective. Therefore, it is necessary to consider whether the constraint condition has a problem, or the model itself has a problem. Therefore, a new approach is proposed to solve this problem, and the specific ideas are as follows:

In the constraint condition of $C^2R$ model, when the evaluated decision unit $DMU_j$ is not considered, and only the $j^{th}$ decision unit is compared with all the other decision-making units in the sample, then the relative effective decision unit can be used to compare (not including $DMU_j$ itself) or sort as the efficiency value of the calculated result may be greater than 1.

After removing a constraint, the improved $C^2R$ model is:

$$\begin{align*}
\min & \theta - \varepsilon (e^T S^- + e^T S^+) \\
\sum_{j=1, j \neq 0}^n X_j \lambda_j + S^- = \theta X_{j0} \\
\sum_{j=1, j \neq 0}^n Y_j \lambda_j + S^+ = Y_{j0} \\
\lambda_j & \geq 0, j = 1, 2, \ldots, n \\
\theta & \geq 0, S^- \geq 0, S^+ \geq 0
\end{align*}$$  \hspace{1cm} (8)

Among them, $DMU_j$ reconstructs an effective combination of decision-making units $\lambda_j$, indicating the combination proportion of the $j$ decision-making unit, $\theta$ is the effective value of decision-making unit $DMU_j$, $\varepsilon$ is infinitely small volume, and usually taken to be $10^{-6}$.

$$\varepsilon = (1, 1, \ldots, 1)^T \subset E^m, e = (1, 1, \ldots, 1)^T \subset E^s;$$  \hspace{1cm} (9)

$S$ is the input relaxation vector.
\[
S = \begin{bmatrix}
4.3945 & 0 & 0 & 0 & 0 & 0 & 10.1111 \\
3.9179 & 0.3772 & 0 & 1390.3044 & 1.1303 & 1.0351 & 0 \\
0 & 3.4729 & 0 & 3189.1259 & 13.0203 & 0 & 101.005 \\
811.8264 & 0 & 0 & 1328844.0131 & 0 & 249.2103 & 10112.4521
\end{bmatrix}
\]

(10)

\[
S^* \text{ is the output remaining vector,}
\]

\[
Z = (0.9430 \ 0.3024 \ 0.4866 \ 0.1300 \ 0.6482 \ 0.3260 \ 0.1281)
\]

(11)

Calculated target function value:

Through the analysis of the input and output data, the DEA model can be used to calculate the quantitative index of the efficiency of each decision-making unit, and then the quantitative index can be used to sort the decision-making unit and find out the most efficient decision-making unit. The quantitative index can also be used to evaluate each decision-making unit to assess whether the scale of the investment is appropriate; or to adjust the correct direction and extent of input and output.

Table 4. Comprehensive Evaluation Results of DEA Method.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Program 1</th>
<th>Program 2</th>
<th>Program 3</th>
<th>Program 4</th>
<th>Program 5</th>
<th>Program 6</th>
<th>Program 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrate Score</td>
<td>0.9430</td>
<td>0.3024</td>
<td>0.4866</td>
<td>0.1300</td>
<td>0.6482</td>
<td>0.3260</td>
<td>0.1281</td>
</tr>
</tbody>
</table>

From the integrated score in Table 4, we can see that the most optimal three programs proposed by DEA are as follows: program 1 (foam drainage), program 5 (work-over rig pumping) and program 3 (vehicle-mounted air lift). On the other hand, the worst three process programs are: program 2 (capillary tube), program 4 (coiled tubing) and program 7 (vortex tube).

Conclusions

In this paper, the data of drainage gas recovery in 11 shallow-middle gas fields in western Sichuan gas field are studied, and many technologies of drainage gas recovery at home and abroad are analyzed, and seven kinds of process programs are used as alternatives. According to the geological characteristics of the current gas wells, the water generation mechanism of gas pools and the water production characteristics of gas wells, the comprehensive evaluation indexes of the drainage gas recovery technologies in the middle-shallow gas pools in western Sichuan Province.

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