



# Application of Lorenz-curve model to stratified water injection evaluation



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**Abstract:** To evaluate the effect of stratified water injection accurately during different development stages, a Lorenz-curve model was constructed upon a modified four-parameter Sarabia-Lorenz-curve model with water injectivity test data over years, and the relationship between accumulative perforated sandstone thickness and injected water volume of single wells was described by the model. Three evaluation indexes, dimensionless water injectivity intensity, vertical sweep efficiency and water-injection non-balanced degree, and their calculation were presented. Dimensionless water injectivity intensity is used to evaluate the distribution and balanced degree of water injectivity intensity, vertical sweep efficiency is the proportion of oil layers that produce oil, and water-injection non-balanced degree illustrates the overall water-injection balanced condition, then the model is solved by particle swarm optimization algorithm. Thirty-eight stratified water injection wells were evaluated in the Daqing Xingshugang oilfield. And the factors influencing the effect of water injection in single wells were studied considering segments construction, water allocation projects and reservoir physical properties. Finally, technological limits of stratified water injection were proposed under extreme high water-cut and recovery.

**Key words:** stratified water injection; Lorenz-curve model; dimensionless water injectivity intensity; water-injection non-balanced degree; vertical sweep efficiency; technological limits of layering

## Introduction

Chinese multilayer reservoir have reached the double-high stage (high recovery more than 80% and high water-cut more than 90%) after long-time waterflooding development<sup>[1]</sup>. The main development performances are: (1) Ratio of effective waterflooding producers is lower, and one-way effective waterflooding wells account for a larger proportion in all the effective producers. (2) Thin and poor oil layers have lower producing degree. (3) Sweeping characteristics in oil-layers differ widely, and are affected by a variety of factors, dominant flowing paths may exist<sup>[2-3]</sup>. Fine stratified water injection (FSWI) generally focuses on subdivision and regrouping of sand units in main thick oil-layers and many kinds of low-permeability thin oil-layers in the double-high stage, which has become the primary waterflooding measure to enhance recovery at present<sup>[4-6]</sup>. However, the water absorption effect of oil-layers with different FSWI wells are quite different, so many researchers have tried to evaluate the wells' fluid

production and water absorption profiles qualitatively by analyzing the oil production increment. However, due to the complex relationship between injection and production and big variation of production and injection profiles, existing qualitative evaluation methods are not reliable, unable to find the factors affecting stratified waterflooding effect, and unable to sort out reasonable segment modes and technical limits. Therefore, in this study, Lorenz-curve is applied to construct models for stratified water injection evaluation<sup>[7-8]</sup>, three indexes, dimensionless water injectivity intensity, vertical sweep efficiency and water-injection unbalanced degree, are advanced, 38 FSWI wells in Xing-6 block of Xing Shugang oilfield are evaluated, and technological limits of layering segments are given.

## 1. Construction of the evaluation model and indexes based on Lorenz-curve

First, all water-injection profile data over the years were analyzed, and perforated sand thickness and water-injection

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volume of every oil-layers were ordered by injectivity intensity from low to high, to get the cumulative perforated sandstone thickness ratio and cumulative water-injection volume ratio as actual data points, and then extended Sarabia Lorenz-curve was taken to match the data points<sup>[9–11]</sup>.

$$\begin{cases} H_n(z_{i,j}) = 1 & (n-1)\Delta z < z_i < n\Delta z \\ H_n(z_{i,j}) = 0 & z_i \leq (n-1)\Delta z, z_i \geq n\Delta z \end{cases} \quad (1)$$

Equation 1 is the relationship model between cumulative perforated sandstone thickness ratio and cumulative water-injection volume derived from extended Sarabia Lorenz-curve. Dimensionless water injectivity intensity, vertical sweep efficiency and water-injection unbalanced degree are advanced based on Equation 1 to evaluate water-injection intensity, swept oil-layer thickness ratio and general water-injection balanced condition of every oil layer quantitatively.

### 1.1. Dimensionless water-injection intensity

Water-injection intensity is a main index to reflect the water absorption ability of oil-layers to meet the demand of oil production, the changing pattern of water-injection intensity has a strong correlation with physical characteristics and productivity variations of oil-layers<sup>[12]</sup>. Therefore, “dimensionless water-injection intensity” is introduced to evaluate the water-injection intensity and water-injection intensity distribution pattern of each oil layer. The dimensionless water-injection intensity is the differential coefficient of cumulative water-injection volume to cumulative perforated sand thickness ratio, its calculation formula is shown below:

$$L'(p) = \alpha p^{\alpha-1} \left[ 1 - (1-p^\gamma)^\beta \right]^\eta + \eta \beta \gamma p^{\alpha+\gamma-1} \left[ 1 - (1-p^\gamma)^\beta \right]^{\eta-1} (1-p^\gamma)^{\beta-1} \quad (2)$$

Dimensionless water-injection intensity unbalanced degree is the fluctuation level around the average water-injection intensity in the scope of cumulative perforated sand thickness ratio, and the index is calculated by Equation 3.

$$I = \int_0^1 |L'(p) - \overline{L'(p)}| dp = \int_0^1 |L'(p) - 1| dp \quad (3)$$

Fig. 1 shows the schematic curves of dimensionless water-injection intensity, in which unbalanced degree is represented as the polygon area (such as the sum of blue and yellow acreages) where the dimensionless water-injection intensity curve (the blue curve) intersected with average line (constant value 1). Besides, the distribution pattern of water-injection intensity is reflected by the shape of the dimensionless water-injection intensity curve. When the intersection acreage is smaller, and the intersection point value is low (as shown in the purple line), the dimensionless water-injection intensity increases rapidly first, and then becomes smooth, so the shape of the curve is convex, which means the water-injection intensity of all oil-layers is more balanced, and the water-injection effect is better than the other two curves

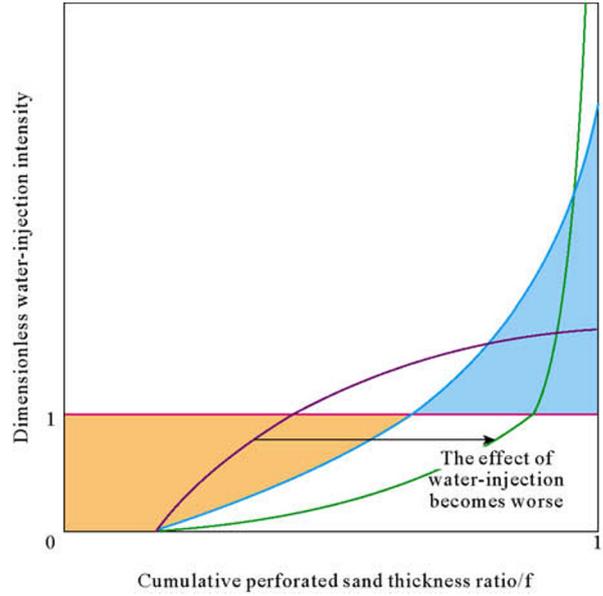


Fig. 1. Schematics of dimensionless water-injection intensity curves.

(blue and green curves). On the contrary, when the intersection acreage is larger, and the intersection point value is big (as the green line shown in Fig. 1), the dimensionless water-injection intensity increases slowly first, and then increases rapidly, so the shape of the curve is concave, which means the water-injection intensity of oil-layers is more unbalanced, and the water-injection effect is worse than the other two curves (blue and purple curves).

### 1.2. Vertical sweep efficiency

Vertical sweep efficiency is defined as the ratio of vertical water-injection oil-layer thickness to whole perforated oil sand thickness in a water well, reflecting the overall producing status of the oil layer. If an oil layer with very small water-injection volume and very weak water-injection intensity is regarded as not producing effectively, when water-injection volume and dimensionless water-injection intensity are introduced as two conditions (Equation 4) according to the statistic laws of actual test data in Daqing La-Saxing oilfield.

$$\begin{cases} L(p) \geq 0.02 \\ L'(p) \geq 0.30 \end{cases} \quad (4)$$

The effective waterflooding oil-layers are identified by Equation 4 with two restrictions, so the perforated sand oil-layer thickness proportion meet the conditions is the vertical sweep degree of FSWI wells.

### 1.3. Water-injection unbalanced degree

Water-injection unbalanced degree is the acreage of surrounding area (yellow area in Fig. 2) between Lorenz-curve and absolutely uniform line, which can reflect the subtle and continuous changing of unbalanced degree of every oil-layer, it is calculated with Equation 5.

$$G = 2 \int_0^1 [p - L(p)] dp = 1 - 2 \int_0^1 L(p) dp \quad (5)$$

The larger the water-injection unbalanced degree, the big-

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