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Research Article

Rate Decline Analysis for Horizontal Wells with Multiple Sections

Jiazheng Qin,[1,2] Shiqing Cheng,[1,2] Youwei He,[1,2] Dingyi Li,[1,2] Jia Zhang,[1,2] Dong Feng,[1,2] and Haiyang Yu[1,2]

[1] *State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, China*
[2] *MOE Key Laboratory of Petroleum Engineering, China University of Petroleum, Beijing 102249, China*

Correspondence should be addressed to Shiqing Cheng; chengsq@cup.edu.cn

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The widely used application of horizontal well makes it significant to effectively evaluate rate performance of horizontal well in oil and gas reservoir. However, most models in previous work only focus on rate decline analysis (RDA) of horizontal well with single section (HWSS); they hardly address the problem that production rate distributes nonuniformly along horizontal wellbore in analyzing rate transient behaviors. However, only some horizontal segments contribute to the total production rates, and the production of each section along horizontal wellbore is not the same in fact, which may be caused by reservoir heterogeneity, selective completion, and nonuniform formation damage along horizontal wellbore. Therefore, the effect of these phenomena on rate decline characteristics cannot be ignored. The aim of this paper is to propose an analytical model to investigate transient rate response of a horizontal well with multiple sections (HWMS). The compound type curves, including the normalized production curve, the normalized production integral curve, and the production integral derivative curve, are developed to distinguish the different cases. The influences of some sensitive parameters on decline curves are further discussed. Results show obvious differences on the decline curves between the HWMS and HWSS. The parameters are sensitive on decline curves, which explore the feasible application on production performance evaluation and parameters interpretation through history matching the production data with the compound type curves in this paper.

1. Introduction

In the past decades, horizontal wells have been widely used in exploration and development of low permeability reservoirs and unconventional reservoirs [1–7]. Rate decline analysis for oil and gas reservoirs is needed for well performance evaluation and reservoir characterization [8]. Arps [9] proposed a series of decline charts to make it convenient for decline curves extrapolation. Then, Fetkovich [10] developed theoretical model and log-log curves to demonstrate both infinite and finite reservoir solutions. To analyze rate decline data where pressure drop and flow rate vary significantly, Blasingame [11] established method for transforming variable-rate system into equivalent constant system using material balance time function.

Many researchers investigated transient rate behavior of horizontal wells. Pratikno et al. [12] provided new type curves for rate decline analysis of fractured well. For analyzing tight oil reservoir, Clarkson and Pedersen [13] provided a method which combines traditional techniques (e.g., flow regime analysis, analytical model history matching, and type curve matching). Duong [14, 15] developed a novel approach to predict future rate for fracture-dominated well in unconventional reservoirs. With considering slippage and desorption in shale gas reservoir, Nobakht et al. [16] established an analytical methodology to analyze rate transient behavior. Belyadi et al. [17] evaluated the productivity of Marcellus Shale wells based on rate transient analysis. On the basis of the dynamic drainage area concept, Qanbari and Clarkson [18] developed a new rate-transient-analysis technique for shale reservoirs. Kuchuk et al. [19] presented the rate decline response of fractured horizontal wells for both conventional and unconventional formations.

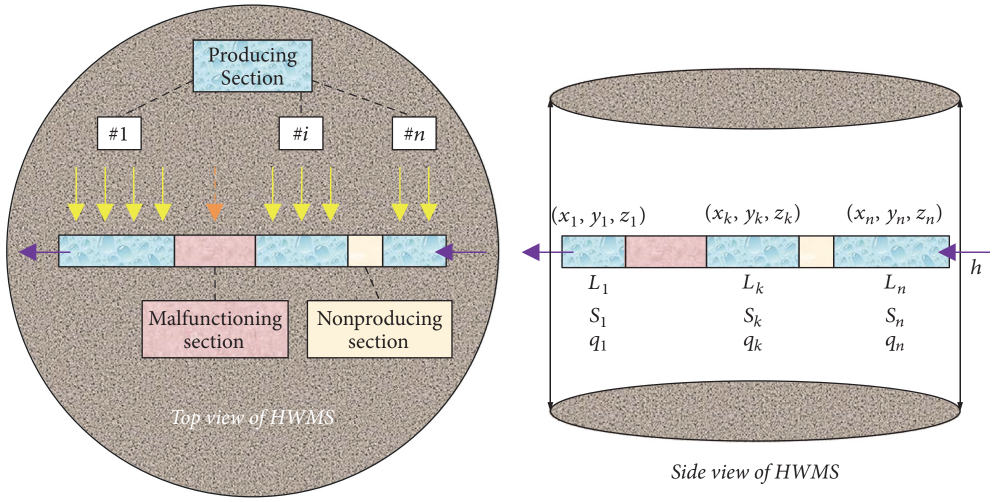

Figure 1: Physical model of HWMS (top view and side view).

In the last decade, numerous research works have been presented on RDA of horizontal wells [20–27]. Although most models in previous study focus on rate decline analysis with one whole section, they did not specifically address the problem that production rate distributes nonuniformly along horizontal wellbore. This may be caused by several reasons. On one hand, due to selective completion, total production rate is contributed from less than the entire well interval. On the other hand, even if the entire well interval is open, on account of reservoir heterogeneity and nonuniform formation damage, production rate of each section along horizontal wellbore is not the same. Some of horizontal sections have little or no contribution. Since this phenomenon exists in horizontal wells with selective completion and open-hole completion, when analyzing transient rate behavior, nonuniform distribution of parameters subject to each section (e.g., length, production rate, skin factor, and location) should be taken into consideration [28–30].

Pressure transient analysis (PTA) is a reliable method for evaluating well performance and reservoir characteristics of wells with multiple sections. Kamal et al. [31] presented an analytical model which allows for a horizontal well to consist of multiple sections. A new flow regime was found, which behaves as a horizontal line with the value of 0.5 divided by number of horizontal sections on pressure-derivative curve. Other PTA models are proposed in different works [32–36]. He et al. [37] proposed a method for estimating malfunctioning horizontal wellbore through bottom hole pressure data. Qin et al. [38] developed novel approach to evaluate nonuniform production distribution of multifractured horizontal wellbore based on PTA. During past years, although plenty of work has been developed for PTA of horizontal wells and multifractured horizontal wells with multiple sections [39–43], rate decline analysis of HWMS is still rarely documented.

The major objective of this paper is to establish an analytical model for analyzing transient rate behavior of HWMS. The effects of some sensitive parameters on decline curves are further investigated (i.e., production rate distribution along wellbore, number of horizontal sections, length of horizontal sections, and spacing between adjacent horizontal sections).

2. Physical Model of Horizontal Well with Multiple Sections

Figure 1 illustrates the physical model of HWMS (top view and side view). Major assumptions are as follows:

(i) Formation is circular-bounded with a constant thickness h, porosity ϕ, horizontal permeability k_h, vertical permeability k_v, initial pressure p_i, and total compressibility C_t.

(ii) The HWMS consists of n sections. Due to formation damage, each section owns specific properties (e.g., length L_k, production rate q_k, and skin factor S_k).

(iii) The fluid is assumed to be single-phase oil or gas in this model. Total production rate equals to q.

(iv) The gravity effect and capillarity effect are negligible.

3. Solution of HWMS Model

In the circular-bounded reservoir, the analytical solution for pressure drop of HWMS at any point can be derived on the basis of the instantaneous source solutions raised by Gringarten and Ramey [44] and Newman product method [45].

Assuming that an HWMS is located in a circular-bounded formation, horizontal wellbore can be regarded as continuous-line-sources with length of L. Through the integration of point-source functions, the line-source solutions can be derived.

For a single point source in the infinite-slab reservoir, it can be considered as a result of plane sources in three different directions (x-, y-, and z-).

By using Newman product method, the point-source function can be obtained:

$$G(x,y,z,t-\tau) = \frac{dV}{\phi C_t} \bullet \frac{1}{4\pi\eta_h(t-\tau)} \exp\left[-\frac{(x-x_w)^2+(y-y_w)^2}{4\eta_h(t-\tau)}\right] \bullet \exp\left[-\frac{(z-z_w)^2}{4\eta_v(t-\tau)}\right] \bullet \frac{1}{\sqrt{4\pi\eta_v(t-\tau)}} \quad (1)$$

$$\eta_h = \frac{k_h}{\phi\mu C_t} \quad (2)$$

$$\eta_v = \frac{k_v}{\phi\mu C_t} \quad (3)$$

$$\beta = \sqrt{\frac{\eta_v}{\eta_h}} \quad (4)$$

where dV represents flow rate per volume. η_h and η_v are diffusivity in horizontal and vertical directions, respectively.

Through the integration of point-source function, the line-source solution is given by

$$\widetilde{p}(x,y,t) = p_i - \frac{ds}{\phi C_t} \bullet \int_{x_w-L/2}^{x_w+L/2} \frac{1}{2[\pi\eta_v(t-\tau)]^{1/2}} \exp\left[-\frac{(x-x')^2}{4\eta_h(t-\tau)}\right] dx' \bullet \frac{1}{4\eta_h(t-\tau)} \exp\left[-\frac{(y-y_w)^2}{4\eta_h(t-\tau)} - \frac{(z-z_w)^2}{4\eta_v(t-\tau)}\right] \quad (5)$$

where ds represents rate per unit length when t equals to τ.

When there is a continuous flow with the rate of q_k from the *k-th* section located at point (x_k, y_k, z_k), the pressure drop at point (x, y, z) can be expressed as

$$\Delta p_k(x,y,z,t) = \frac{1}{\phi C_t}\frac{q_k}{2\pi L_k}\int_0^t G_x G_y G_z d\tau \quad (6)$$

$$G_x = \frac{1}{2}\left\{\operatorname{erf}\left[\frac{L_k/2+(x-x_k)}{\sqrt{4\eta_h\tau}}\right] + \operatorname{erf}\left[\frac{L_k/2-(x-x_k)}{\sqrt{4\eta_h\tau}}\right]\right\} \quad (7)$$

$$G_y = \frac{1}{\sqrt{4\pi\eta_h\tau}}\exp\left[-\frac{(y-y_k)^2}{4\eta_h\tau}\right] \quad (8)$$

$$G_z = \frac{1}{h^*}\left[1 + 2\sum_{n=1}^{\infty}\exp\left[-\frac{n^2\pi^2\eta_v\tau}{(h^*)^2}\right]\cos\left(\frac{n\pi z_k}{h}\right)\cos\left(\frac{n\pi z}{h}\right)\right] \quad (9)$$

$$h^* = h\sqrt{\frac{k_h}{k_v}} = \frac{h}{\beta} \quad (10)$$

where h^* means the formation thickness considering permeability anisotropy and β is anisotropy coefficient.

Through the principle of superposition, pressure drop caused by multiple sections can be obtained:

$$\Delta p(x,y,z,t) = \frac{1}{\phi C_t}\sum_{k=1}^{n}\frac{q_k}{2\pi L_k}\int_0^t G_x G_y G_z d\tau \quad (11)$$

denoting

$$q = \sum_{k=1}^{n} q_k \quad (12)$$

The dimensionless length and production rate of the k-th section, dimensionless length of horizontal well, and dimensionless time are defined as

$$L_{kD} = \frac{L_k}{L}; \quad q_{kD} = \frac{q_k}{q}; \quad t_D = \frac{k_h t}{\phi\mu C_t L^2} = \eta_h\frac{t}{L^2} \quad (13)$$

Other dimensionless variables are defined as follows:

$$p_D = \frac{2\pi k_h h^*[p_i - p(x,y,z,t)]}{q\mu}; \quad C_D = \frac{C}{2\pi h^*\phi C_t L^2}; \quad h_D^* = \frac{h^*}{L}; \quad h_D = \frac{h}{L}; \quad x_D = \frac{x}{L}; \quad y_D = \frac{y}{L}; \quad z_D = \frac{z}{L}; \quad x_{kD} = \frac{x_k}{L}; \quad y_{kD} = \frac{y_k}{L}; \quad z_{kD} = \frac{z_k}{L}; \quad (14)$$

As a result, dimensionless pressure drop of an HWMS with n sections is given by

$$p_D(x_D, y_D, z_D, t_D) = \frac{\sqrt{\pi}}{2} \cdot \sum_{k=1}^{n} \frac{q_{kD}}{L_{kD}} \int_0^{t_D} G_{xD} G_{yD} G_{zD} d\tau_D \tag{15}$$

$$G_{xD} = \text{erf}\left[\frac{L_{kD}/2 + (x_D - x_{kD})}{\sqrt{4t_D}}\right] + \text{erf}\left[\frac{L_{kD}/2 - (x_D - x_{kD})}{\sqrt{4t_D}}\right] \tag{16}$$

$$G_{yD} = \frac{1}{\sqrt{t_D}} \exp\left[-\frac{(y_D - y_{kD})^2}{4t_D}\right] \tag{17}$$

$$G_{zD} = 1 + 2\sum_{n=1}^{\infty} \exp\left[-\frac{n^2\pi^2\beta^2 t_D}{(h_D^*)^2}\right] \cos\left(\frac{n\pi z_{kD}}{h_D}\right) \cdot \cos\left(\frac{n\pi z}{h_D}\right) \tag{18}$$

Since formation damage caused by drilling and completion cannot be ignored, dimensionless pressure drops resulted by skin effect can be written as

$$p_S(x_D, y_D, z_D, t_D) = \sum_{k=1}^{n} \frac{q_{kD}}{L_D} S_k \tag{19}$$

$$p_{SD}(x_D, y_D, z_D, t_D) = p_D(x_D, y_D, z_D, t_D) + p_S(x_D, y_D, z_D, t_D) \tag{20}$$

By converting solution into Laplace domain, dimensionless pressure drop with considering the effect of wellbore storage can be expressed as

$$p_{CD}(C_D, u) = \int_0^{t_D} \left[1 - C_D \frac{dp_D}{dt_D}\right] \frac{dp_{SD}(t-\tau)}{d\tau} d\tau \tag{21}$$

On the basis of Laplace transformation, analytical solution for unsteady-state pressure drop of HWMS with incorporating skin effect and wellbore-storage effect at any point can be derived:

$$\overline{p}_{CD}(C_D, S, u) = \frac{\overline{p}_D}{1 + C_D u^2 \overline{p}_D} \tag{22}$$

where $\overline{P}_{CD}$ and $\overline{P}_D$ represent the dimensionless pressure with and without considering wellbore storage, respectively, and u is the Laplace transform variable. Through numerical inversion algorithm developed by Stehfest [46] and Duhamel principle [47], rate solution of HWMS can be obtained.

The circular-boundary effect can be taken into consideration by using the method from Pratikno et al. [12]:

$$(\overline{p}_{CD})_{boundary\ effect} = \frac{1}{u} \frac{1}{\sqrt{u}} \frac{K_1(\sqrt{u} r_{eD})}{I_1(\sqrt{u} r_{eD})} \int_0^{\sqrt{u}} I_0(z)\, dz \tag{23}$$

By using Duhamel principle [47], dimensionless rate solution of HWMS under constant pressure located in circular-bounded formation in Laplace space can be expressed as

$$\overline{q}_D(s) = \frac{1}{s^2 \overline{p}_{CD}(s)} \tag{24}$$

$\overline{q}_D$ can be converted into the real space using the Stehfest inversion algorithm [46].

Furthermore, three types of rate-material balance time curves can be plotted.

(i) The normalized dimensionless decline production curve (q_{Dd})

(ii) The normalized dimensionless decline production integral curve (q_{Ddi})

(iii) The dimensionless decline production integral derivative curve (q_{Ddid})

4. Model Comparison

In this part, Blasingame type curves are developed by use of HWMS model proposed in this paper and HWSS model in previous study.

For HWSS model, an HWSS with length of L and constant rate of q is located in circular-bounded reservoir. Since HWSS only consists of one section, in this case, n equals one. For HWMS model, length of each section equals 0.1L and production rate of each section is q/n. Two cases are further discussed (i.e., n=1, n=5). When n equals 1, producing section is located at the heel of horizontal wellbore. When n equals 5, sections are distributed uniformly along wellbore.

By comparing type curves from HWMS model with that from HWSS model, clear distinctions can be observed on Blasingame compound type curves except for the boundary-dominated flow period, shown in Figure 2. Three kinds of curves (i.e., q_{Dd}, q_{Ddi}, and q_{Ddid}) belonging to compound type curves are shown in Figure 3. Compared to Figures 3(a) and 3(b), the use of production integral derivative smooths the derivative curve of measured data and makes it easier to identify different features as shown in Figure 3(c). Therefore, it is necessary and significant to establish the RDA model of HWMS to analyze the rate transient behavior, which enable us to better evaluate production performance.

5. Effect of Sensitive Parameters on Decline Curves

To understand the effects of main parameters on rate transient behaviors of a HWMS, we develop the Blasingame compound type curves to perform the sensitivity analysis through the RDA model proposed in this paper (i.e., production rate distribution along wellbore, number of horizontal sections, length of horizontal sections, and spacing between adjacent horizontal sections).

5.1. Production Rate Distribution along Wellbore. Dimensionless production rate is defined as the production rate of each

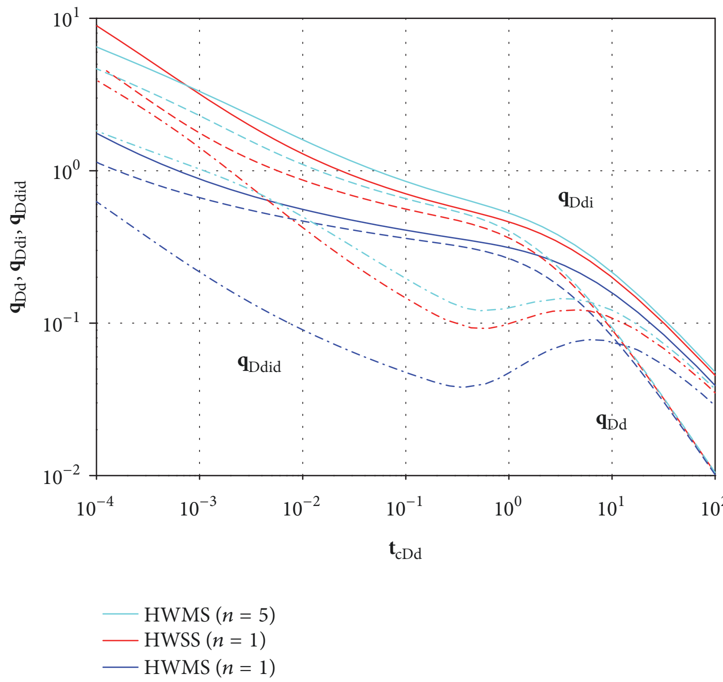

FIGURE 2: Blasingame compound type curves of HWMS and HWSS.

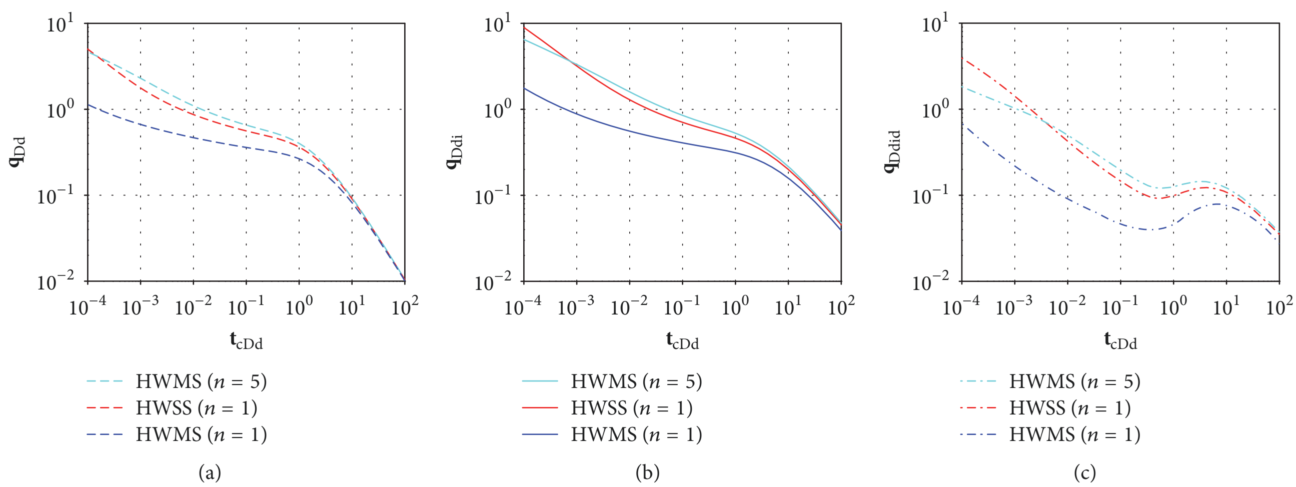

FIGURE 3: Blasingame type curve according to the solution of constant rate: (a) q_{Dd}; (b) q_{Ddi}; (c) q_{Ddid}.

producing section divided by total production rate of all sections (q_{kD}= q_k/q_{total}). A horizontal well with length of L consists of three producing sections, and length of each section equals 0.1L. Three sections located at the heel, middle, and toe of wellbore, respectively, and production rate are unequal for these sections. Figure 4 shows the compound type curve. The red curves represent the normalized dimensionless decline production curves (q_{Dd}), the green curves means the normalized dimensionless decline production integral curve (q_{Ddi}), and the blue curves denote the dimensionless decline production integral derivative curve (q_{Ddid}). The effects of production rate distribution along wellbore on production characteristic are obvious especially for the production integral derivative curve during the transient flow regime. The results tell us that we can estimate the production distribution of different locations along horizontal wellbore through the history matching of long-term production data. If the field production data can match with these three curves at the same time, the results can be reliable.

5.2. Number of Horizontal Sections. For number of horizontal sections, five cases are further discussed (i.e., n=1, 2, 3, 4, 5). In all cases, each section has the same length (L_k= 0.1L), production rate (q_k= q_{total}/n), and skin factor, respectively. All producing sections distribute uniformly along wellbore. The compound type curves of different numbers of horizontal

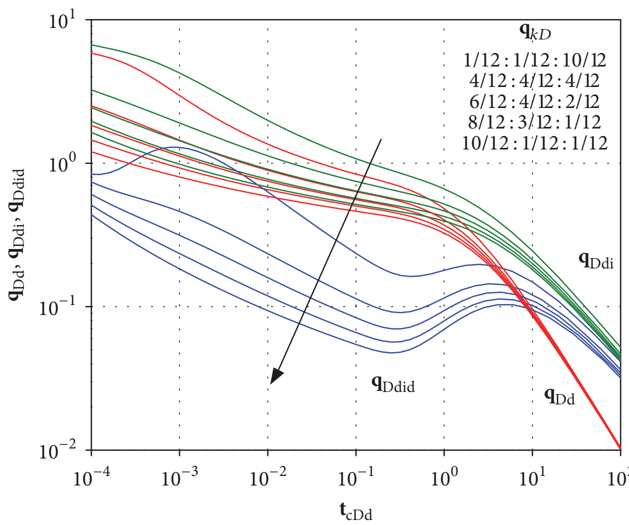

FIGURE 4: The effect of rate distribution on type curves.

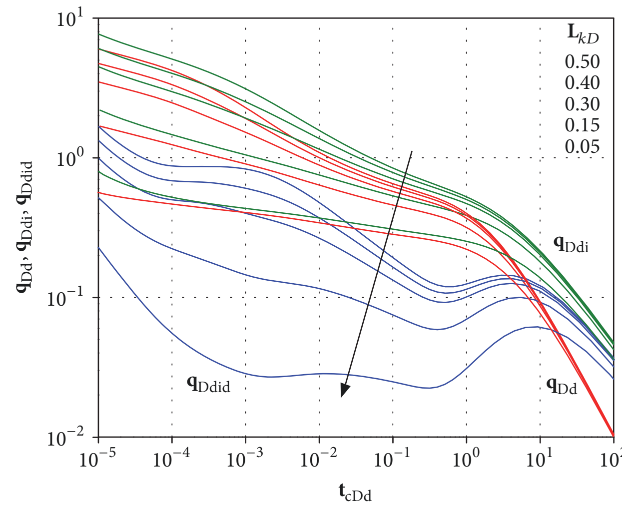

FIGURE 6: The effect of length of two sections on type curves.

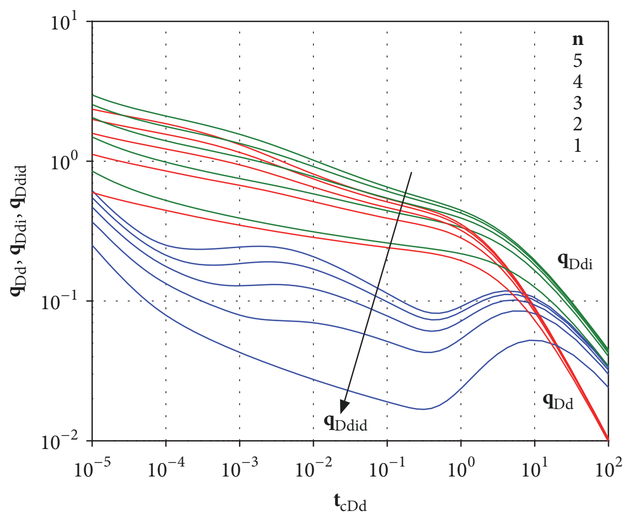

FIGURE 5: The effect of number of horizontal sections on type curves.

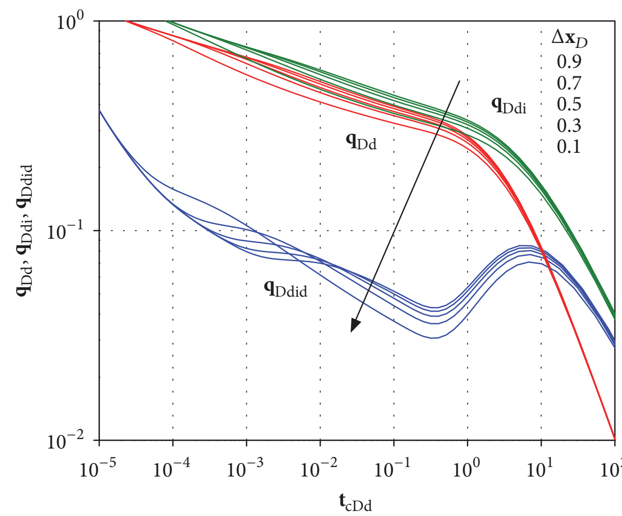

FIGURE 7: The effect of spacing between adjacent horizontal sections on type curves.

sections are shown in Figure 5. As the number of horizontal sections decreases, all curves move downward. There exist big differences between the results for n=1 and n=5 during the transient flow period. Although the distinctions between the normalized production curves (q_{Dd}) and the normalized production integral curve (q_{Ddi}) are not obvious enough, the production integral derivative curves (q_{Ddid}) show clear differences among them. Therefore, the number of horizontal sections is sensitive and can be determined through matching the production data with the compound type curves in this paper.

5.3. Length of Horizontal Sections. Dimensionless length of horizontal sections equals length of each section divided by length of horizontal wellbore ($L_{kD}= L_k/L$). Two sections with the same dimensionless length are located at the heel and toe of horizontal well. Both sections have the same production rate, skin factor, etc. Figure 6 shows the effect of length of horizontal sections on type curves. The normalized production curves and the normalized production integral curve are quite different especially when dimensionless length of horizontal sections become smaller. The production integral derivative curves differ from other cases for different L_{kD}, which is benefit of estimating effective producing length of the horizontal well.

5.4. Spacing between Adjacent Horizontal Sections. Dimensionless spacing between adjacent horizontal sections is defined as the spacing between adjacent horizontal sections divided by length of horizontal wellbore ($\Delta x_D = \Delta x/L$). Five cases are designed to discuss the influences of dimensionless spacing on decline curves. As the distance from the second producing section to the heel becomes farther, decline types move up, shown in Figure 7. Though the influences of spacing between horizontal sections on type curves are not obvious compared to other parameters, it is possible for us to distinguish them based on the production integral derivative curves during the transient flow regime.

6. Conclusions

This paper establishes the RDA model of a HWMS and the compound rate decline type curves to analyze the effect of production distribution, number and length of producing horizontal sections, and spacing between sections on rate transient behaviors.

(1) Since different horizontal segments make unequal contribution to total production rates in fact, the effect of these phenomena on rate decline behaviors should be considered.

(2) The effects of production rate distribution along wellbore on rate characteristic are obvious especially for the production integral derivative curve during the transient flow regime, which makes it possible to estimate the production distribution through the history matching of production data.

(3) The normalized production curves and the normalized production integral curve are quite different especially when dimensionless length of horizontal sections become smaller. The production integral derivative curves differ from other cases for different L_{kD}, which is benefit of estimating effective producing length of the horizontal well.

(4) Although the distinctions between the normalized production curves and the normalized production integral curve are not obvious, the production integral derivative curves show clear differences among them. Therefore, the number of horizontal sections can be determined through matching the production data.

In conclusion, the proposed RDA model enables engineers to evaluate the rate performance of horizontal wells and interpret reservoir and well parameters more effectively and accurately (e.g., estimating the production distribution of different locations along horizontal wellbore and effective producing length, permeability, well controlled area and reserves, and skin factor) through the history matching of long-term production data. If the field production data can match well with these three curves at the same time, the results can be reliable.

Nomenclature

C: Wellbore-storage coefficient, atm^{-1}
C_D: Dimensionless wellbore-storage coefficient
C_t: Total compressibility, atm^{-1}
h: Formation thickness, cm
h^*: Formation thickness considering permeability anisotropy, cm
$h_D{}^*$: Dimensionless formation thickness considering permeability anisotropy
k_h: Horizontal permeability, D
k_v: Vertical permeability, D
L: Length of horizontal well, cm
L_D: Dimensionless length of horizontal well
L_k: Length of the k-th section, cm
L_{kD}: Dimensionless length of the k-th section
n: Number of horizontal sections, dimensionless
p: Pressure, atm
p_{CD}: Dimensionless pressure drop with considering wellbore-storage effect
p_D: Dimensionless pressure drop
p_i: Initial reservoir pressure, atm
p_S: Dimensionless pressure drop caused by skin effect
p_{SD}: Dimensionless total pressure drop with considering skin effect
q: Total production rate, cm^3/s
q_{Dd}: Normalized dimensionless decline production
q_{Ddi}: Normalized dimensionless decline production integral
q_{Ddid}: Normalized dimensionless decline production integral derivative
q_k: Production rate of the k-th section, cm^3/s
q_{kD}: Dimensionless production rate of the k-th section
s: Laplace-transformation parameter
S: Skin factor
S_k: Skin factor of the k-th section
t: Time, s
t_D: Dimensionless time
u: Laplace transform variable
x, y, z: Cartesian coordinates
x_D, y_D, z_D: Dimensionless Cartesian coordinate
x_k, y_k, z_k: Coordinates of the center of the k-th section
x_{kD}, y_{kD}, z_{kD}: Dimensionless coordinates of the center of the k-th section
ϕ: Porosity, fraction
η_h: Diffusivity in horizontal direction, cm^3/s
η_v: Diffusivity in vertical direction, cm^3/s
μ: Fluid viscosity, cP
β: Anisotropy coefficient
τ: Time variable
Δp: Pressure drop caused by all sections
Δp_k: Pressure drop caused by the k-th section
$\overline{p}_{CD}$: Dimensionless pressure in Laplace space with considering wellbore-storage effect
$\overline{p}_D$: Dimensionless pressure in Laplace space without considering wellbore-storage effect
$\overline{q}_D$: Dimensionless rate in Laplace space.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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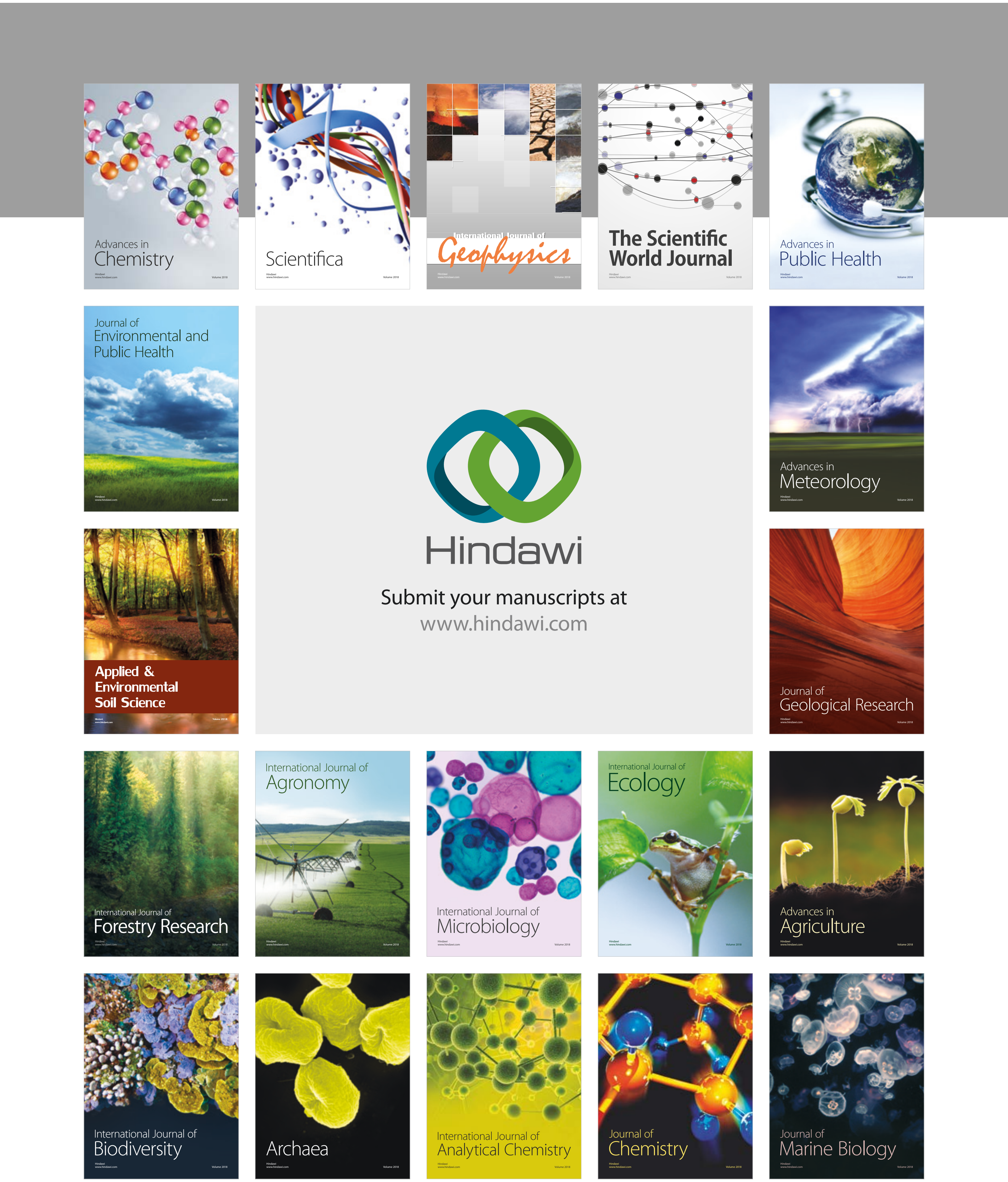
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