Abstract

The pressure response of a well producing a two-layer reservoir with crossflow is examined. Virtually all studies on the response of a well in multilayered systems with crossflow claim that after a few hours of production these systems behave as if they are single-layer systems.

A careful examination of the early-time performance of a well in a reservoir with crossflow indicates that its behavior is remarkably different from that of an equivalent single-layer system and is influenced significantly by the degree of communication. It is important to understand short-time behavior, since the time span of virtually all pressure buildup tests encompasses the duration in which pressure buildup tests encompasses the duration in which a layered reservoir with crossflow may not behave as if it were a single-layer system. Thus, interpretations of pressure buildup data based on single-layer theory can be erroneous.

In this study, we show that the flowing pressure response of a well at early times can be divided into three flow periods. The first period is one in which the reservoir behaves as if it were a stratified (no-crossflow) system. This period is followed by a transitional period. The response of the well during this period depends on the contrast in horizontal permeabilities and on the degree of communication between the layers. During the third period, the reservoir can be described by an equivalent period, the reservoir can be described by an equivalent single-layer system.

An examination of the time ranges of the various flow periods indicates that, unless tests are designed periods indicate that, unless tests are designed properly, most of the interpretable pressure buildup data would properly, most of the interpretable pressure buildup data would be measured during the time the well response is influenced by the transitional period.

The influence of the skin regions on the well response is examined. The significance of the estimate of the skin factor obtained from a pressure test is discussed. We show that the nature and the magnitude of the skin regions and the size of the reservoir determine the applicability of conventional semilog procedures to systems with interlayer communication.

Introduction

The economic consequences of interlayer crossflow are well established in the literature. Several studies have examined the well response in a reservoir with interlayer communication. However, most of these studies have been concerned primarily with the
long-term performance of the well. A reservoir with crossflow can be represented by a single-layer reservoir of equal volume if the flow capacity of the single-layer system is equal to the arithmetic sum of the flow capacities of all layers. Some of these studies also have shown that the early-time response of a well draining a reservoir with interlayer crossflow is similar to the response of a well in a stratified (no-crossflow, commingled) reservoir. Undoubtedly, a transitional period must exist between these two extremes. None of the works cited previously discuss the duration of or the characteristics of the transitional period. If one is interested in short-time testing, such as pressure buildup tests, then it is imperative that the duration of the transitional period and the characteristics of the well response during this period be known. For example, if the duration of the test period is such that the well behaves as if it drains a stratified system or a homogeneous system, then classical well test theories should be applicable. On the other hand, if the test period is such that the transitional period governs the well response, then important questions need to be answered. First, what are the magnitudes of the errors that would result if data during this period are analyzed by conventional procedures? Second, what are the parameters that control the duration of the transitional flow period? Third, is it possible to obtain reservoir characteristics from a pressure buildup test?

None of the studies in the literature considers the influence of the skin regions on the well response. The skin regions have a significant influence on interlayer crossflow. In this study we show that the skin regions can have a dramatic influence on the well response, particularly during early times. We also show that conventional interpretations of flow behavior in the skin region are inadequate if the layers are in communication.

The objective of this paper is to present a thorough examination of the performance of a well in a reservoir with interlayer crossflow. We intend to address the questions raised in the preceding paragraphs. The determination of formation parameters will be discussed. The results obtained here are applicable to both pressure transient tests and production logging. SPEJ
Summary. This paper presents new testing and analysis techniques to obtain individual-layer permeabilities and skin factors for layered reservoirs. The new multilayer testing technique consists of a number of sequential flow tests with a production logging tool that simultaneously measures the wellbore pressure and flow rate at the top of each layer.

Two different analysis techniques are presented to estimate layer parameters. The first technique, which is the logarithmic convolution method, estimates the approximate values of parameters. The second technique, which is the nonlinear least-squares estimation method, improves the first estimates.

It is shown that layer permeabilities and skin factors can be estimated uniquely from simultaneously measured wellbore pressure and flow-rate data that are acquired from all layers sequentially. It is also shown that these individual-layer parameters cannot be estimated from the conventional drawdown- or buildup-test wellbore pressure data. Several synthetic examples are presented to illustrate pressure data. Several synthetic examples are presented to illustrate the application of multilayer testing and analysis techniques.

Introduction

Most oil and gas reservoirs are layered (stratified) to various degrees because of sedimentation processes over long geological times. Layered reservoirs are composed of two or more layers that may have different formation and fluid characteristics. These reservoirs are usually divided into two groups: (1) layered reservoirs without crossflow (commingled systems), where layers communicate only through the wellbore, and (2) layered reservoirs with crossflow, where layers communicate at the contact planes throughout the reservoir. Accurate determination of permeability, skin factor, and pressure for each layer is necessary to understand the reservoir performance. For example, unbalanced depletion of layers with different parameters creates many problems, such as high GOR in high-permeability layers.

Conventional buildup tests from layered reservoirs usually suffer from crossflow between layers, particularly if the layers communicate only through the wellbore and/or the permeability contrast between layers is high. The crossflow problem becomes more severe if the pressure and/or the drainage radius of each zone is different. The wellbore crossflow may continue during the entire period of the buildup test. A false straight line on a period of the buildup test. A false straight line on a semi-log plot may even be observed. In many instances, the pressure data alone may not reveal any information about pressure data alone may not reveal any information about the wellbore or formation crossflow.
Even if crossflow is not a complicating factor, the major problem for layered systems is still the estimation of problem for layered systems is still the estimation of individual-layer permeabilities and skin factors from conventional well tests. The conventional drawdown and buildup tests usually reveal only the behavior of the total system. Furthermore, the behavior of a multi layer formation may not be distinguished from the behavior of a single-layer formation even though a multilayer reservoir may have a distinct behavior without wellbore storage effects.

There are, however, a few special cases where the conventional tests may work. A detailed study of the behavior of two-layer reservoirs with crossflow was done by Prijambodo et al. Unlike many earlier researchers, they investigated the effect of each layer's skin on the semilog straight-line behavior of the two-layer systems without the wellbore storage effect. They also examined limitations of the semilog methods for two-layer systems with many different combinations of vertical and horizontal permeabilities and skin factor with and without crossflow. permeabilities and skin factor with and without crossflow. A different approach for estimating layer parameters by means of optimum test design was investigated by Dogru and Seinfeld. They used a numerical model, but did not include skin and wellbore storage effects. Nevertheless, they show that there are serious problems with the ability to observe and question how well-posed parameter estimation is for layered reservoirs with a parameter estimation is for layered reservoirs with a single transient test.

Most work on layered reservoirs has been the derivation of solutions for boundary-value and initial-value problems, the investigation of sensitivity of solutions to layer parameters (forward problem), and the estimation of the parameters (forward problem), and the estimation of the average flow capacity and skin factor of the total formation from a single transient well test.

We present a new testing technique for layered reservoirs to estimate individual layer permeabilities and skin factors uniquely. This new test will be called a "multilayer test" hereafter. The multilayer testing technique consists of a number of sequential flow tests, with a production logging tool measuring the wellbore pressure and flow rate at the top of each different layer.
Experience with a large number of well tests has shown that the analysis of some field tests using currently available interpretation models is not satisfactory. Marked departure from homogeneous behavior is evident and none of the available heterogeneous models, such as the double porosity models, yields a convincing interpretation. This is particularly apparent when the pressure derivative behavior is examined. In this paper, a new analytical solution is presented that describes the pressure response of a well intercepting a layered reservoir with crossflow. The model is designed to describe a system of alternating beds of relatively high permeability contrast. The interpretation models currently in use (homogeneous reservoir, two layers without crossflow, double porosity reservoir) are shown to be limiting forms of the new solution which is therefore a more general description of transient pressure responses. The layered reservoir behavior is discussed in terms of the pressure and the derivative of pressure. The limits of applicability pressure and the derivative of pressure. The limits of applicability of the homogeneous and the double porosity solutions for analysis of tests in layered formations are clearly defined. The new model is used to analyze an actual field case and a good match is obtained when no other solution is found to be applicable. In addition to the usual well and reservoir parameters (total permeability thickness product, skin and wellbore storage constant), analysis yields quantitative information on the storativity and permeability of the contrasting layers.

Introduction

Well pressure responses, recorded during tests, are interpreted to provide a description of the well condition and various informations on the reservoir. The analysis is carried out on pressure versus time plots, either by identification of straight lines on portions of the data (and determination of parameters of interest from slope and intercept values), or by curve matching on the global response. This last approach considers the pressure data as a whole, including the curvatures present in the plots, and therefore it ensures a higher degree of confidence in the results of interpretation. Curve matching technique is now currently used to analyse a large variety of well and reservoir configurations. As a result of the progress recently observed in pressure gauge technology, pressure data reveal much more information than in the past. Practice of curve analysis in well test interpretation shows that reservoir heterogeneities are very frequently observed. For example, it is not exceptional that long build up tests never reach the homogeneous infinite acting radial flow behavior, traditionally assumed when semi-log straight line analysis is attempted. Taking advantage of the computing facilities now available, even at the wellsie, a new approach as been recently proposed for well test interpretation. It considers not only the pressure response but also the derivative of the pressure. It provides much more characteristic response curves for analysis and in particular amplifies the small variations produced on pressure behavior by reservoir heterogeneities. The use of pressure derivative confirms frequently the need for heterogeneous interpretation models but, on the other hand, the high sensitivity of the derivative curves shows also the limits of the presently available analytical solutions. It is found, in some cases, that none of the usual heterogeneous models provide a
good match on the derivative data plot even when conventional pressure curve analysis seems to reproduce reasonably well the pressure curve analysis seems to reproduce reasonably well the recorded pressure response. In this paper, we will first review briefly several double porosity models used for analysis of heterogeneous formation responses, we will discuss the different hypotheses introduced in their mathematical derivations and will illustrate the difference in shape of the resulting curves. Then, we will propose a new analytical solution for a two layers system with cross-flow, present typical curves and compare them to the classical heterogeneous responses. The applicability of the new model to actual reservoir configurations will be discussed and an example analysis of actual pressure data will be presented.

**DOUBLE POROSITY MODELS:**

Several double porosity solutions have been proposed to describe fissured formation responses. In all cases, two media are considered: one, the fissures system, is of high permeability but does not store much of the fluid in place. The other, the matrix system, has a very low permeability but contains most of the oil. One of the basic assumptions of the double porosity models is that all the oil is produced to the well via the fissures only, hence the matrix system produced to the well via the fissures only, hence the matrix system having no effective connection to the well. In the mathematics, this assumption is implemented by making the permeability to the well for the matrix system zero.
A New Test for Determination of Individual Layer Properties in a Multilayered Reservoir

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Summary. Many wells penetrate several layers, and flow from each layer is often commingled during production or injection. The behavior of pressure transients for layered systems has been studied in detail for pressure transients for layered systems has been studied in detail for two types of systems: (1) layers that are separated by impermeable barriers (no formation crossflow) and (2) layers that communicate in the reservoir. In this work, the general problem of n homogeneous layers, in which any two adjacent flowing layers may or may not be crossflowing in the formation, is solved analytically. Properties, including permeability, porosity, layer thickness, the wellbore skin factor, and the vertical permeability between crossflowing layers, are distinct for each flowing layers. Wellbore storage effects are also included, and solutions are provided for both infinite-acting and bounded systems. The key to finding the individual layer properties in a given reservoir lies in the interpretation of the transient flow rates from each layer following a change of the total flow rate for the well. Pressure transients are also used in the analysis. The limiting forms of the analytic solution are used to identify certain characteristic patterns in the flow-rate transients that provide the means for determining the individual layer properties. The methods used in this analysis are entirely new. An example of the interpretation method is provided.

Introduction

Interest in the behavior of multilayered reservoir systems has prompted a great number of studies in the last 25 years. Only in prompted a great number of studies in the last 25 years. Only in the last 5 years, however, have testing methods begun to provide more than a qualitative grasp on the reservoir description. Table 1 indicates the scope of various information on this subject, listing the relevant papers that have been published in the petroleum literature. A certain oscillation in the perception of the multilayered system is apparent. In particular, the modeling of interlayer formation crossflow has alternated with a focus on "commingled" systems. The latter terminology has generally been reserved for multilayered systems with no communication in the formation, other than through the well. Hence, a distinction must be made between formation crossflow, which can occur only when a nonzero vertical permeability exists between two adjacent layers, and wellbore crossflow, which can occur between any two layers that are penetrated by the wellbore. The earliest rigorous study found for the commingled reservoir system was that of Lefkovits et al. This study, which addressed an arbitrary number of layers with distinct layer properties, including thickness, porosity, permeability, and properties, including thickness, porosity, permeability, and skin, provided an analytic model and a host of practical observations that have served as the basis for much of the work that has followed. Of particular interest were the presentations of both pressure and layer flowrate transients, presentations of both
pressure and layer flowrate transients, the latter of which will be shown in this work to be essential data for evaluation of individual layer properties in a well test. For the commingled system, the model development was extended by Tariq and Ramey, whose contributions included the introduction of wellbore storage and, together with Ref. 36, the first use in the petroleum literature of the Stehfest algorithm for numerical inversion of Laplace transforms. Since that time, use of this algorithm has resulted in numerous practical applications in the well test literature, including this work. The other class of models for multilayered systems involves interlayer formation crossflow. The earliest studies used partial differential equations written in two-dimensional cylindrical coordinates (r-z symmetry). The first known formulation of this type was offered for the no-flow bounded system by Jacquard. The Jacquard solution was computed for two layers by Pottier, who provided observations of the following: drawdown pressure transients for various layer thickness ratios, comparisons with the commingled two-layer pressure transients, layer flow-rate transients for the commingled system, and radial pressure distributions vs. time for the communicating layers and the pressure gradient between them. Drawing from the terminology for dual-porosity systems, formation crossflow in the Jacquard formulation can be called transient interlayer flow. An early study reported by Polubarinova-Kocina and recent models published in Refs. 27 through 30 and 35 have presented the interlayer flow by a pseudosteady-state approximation that reduces the partial pseudosteady-state approximation that reduces the partial differential equations to a system of onedimensional (radial) equations. Refs. 27 and 28 provided observations similar to those of Pottier and extended the formulation to an arbitrary number of layers.
Simulation of Fractures Induced by Produced Water Re-Injection in a Multi-Layer Reservoir

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Abstract

In a recent study a numerical model for Produced Water Re-injection (PWRI) under fracturing conditions was presented [1]. The model was a 2-dimensional analytical fracture growth model and hence only appropriate for constant-height fractures fully penetrating the injection layer, with a "square fracture" option allowing a first order estimate of radial fracture dimensions. In this paper we present a new 3-dimensional fracture growth model which permits the description of elliptical fractures in a multi-layer reservoir with fracture length, height up and height down all potentially growing at different rates.

The pressure field in the formation around a fully contained elliptical fracture will resemble that of a fracture in an unbounded reservoir (i.e. 3D solution), while far into the reservoir it will approach a 2D solution, with a gradual transition between the two limiting cases. Solutions to both of these limiting cases have been developed earlier [2,3]. Here we present a new method which approximates the gradual transition from 3D-elliptical symmetry to 2D-elliptical symmetry with an abrupt transition. In a multi-layer reservoir the model can be applied independently to all the layers if no crossflow between the layers is allowed.

A comparison is presented between the two models which demonstrates that the previous model predicts larger fracture sizes. This is particularly the case if the pressure drop over the filtercake is relatively small.

We also present a new approach to represent plugging within the fracture due to the build-up of filtercake resulting from suspended particulates in the produced water. This new approach allows for flow channels to develop within the filtercake in the fracture, rather than the approach used in the previous study which adopts a parallel-plate flow model and allows uniform growth of filter cake on fracture walls.

A number of PWRI field examples is also presented. The model is very suitable to assess the containment capacity of layered reservoirs, which is demonstrated using a field example of a large reservoir in the Middle East.

Comparisons with Prudhoe Bay data show that our model is not capable of predicting the virtually immediate response to changes in the water quality. The model still assumes that the filtercake properties are determined by the cumulative volume of solids pumped into the formation. This needs to be reviewed and possibly extended to also include immediate effects.
Introduction

In a recent study a numerical model for Produced Water Re-injection (PWRI) under fracturing conditions has been presented [1]. This model fully couples the reservoir engineering aspects and fracture mechanics of the problem. The 2D flow pattern in the reservoir is analytically described using a decomposition in a Fourier series; the fracture mechanics are handled using an equilibrium-growth criterion. The pressure for given fracture length is determined by assuming that the fracture toughness equals the stress intensity factor; the coupling with the flow in the reservoir is established by assuming that the injection rate equals the leakoff rate from the fracture into the reservoir. Important features which are common to both clean and dirty water injection are taken into account, such as backstresses resulting from pore pressure inflation and reservoir cooling, as well as features specific to injection of produced water, such as formation impairment and fracture plugging.