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Full Length Article

A new and simple model for the prediction of horizontal well productivity in gas condensate reservoirs

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ABSTRACT

Horizontal well drilling is a well-established technology to enhance well productivity by increasing reservoir contact compared to that of vertical wells under the same conditions. In gas condensate reservoirs, in addition to the three-dimensional (3D) nature of the flow geometry around the horizontal well, the flow behaviour is further complicated by the phase change and the variation of relative permeability (k_r) due to the coupling (increase in k_r by an increase in velocity or decrease in IFT) and inertia (a decrease in k_r by an increase in velocity) effects. There are no practically attractive simple methods for well productivity calculations that account for these effects. Therefore, as an alternative, numerical simulation of such a complex 3D flow using commercial numerical simulators is usually adopted. This approach requires a 3D fine grid compositional approach which is very demanding, cumbersome and often associated with convergence problems due to numerical instability. Consequently, the introduction of a quick and reliable tool for long term well productivity calculations for gas-condensate systems is the main objective of the present work.

An in-house simulator was developed to realistically simulate the multiphase flow of gas and condensate around horizontal wells. Using this model, a large data bank was then generated covering the impact of a wide range of pertinent geometric and flow parameters on well performance including: well and reservoir geometries, reservoir and bottom-hole pressure, fluid velocity, gas oil ratio and fluid composition.

Based on the results of these simulations, a new method has been proposed to predict the productivity of horizontal wells for gas and condensate systems. In this approach, the flow behaviour of gas and condensate around the well is quantified in terms of the effective wellbore radius of an equivalent open hole that replicates flow around the actual 3D system. The effective wellbore radius varies with fluid properties, velocity and interfacial tension (IFT), reservoir and wellbore conditions. The integrity of the new methodology has also been verified for various fluids and flow conditions.

This approach, included in a simple spreadsheet, can predict the horizontal well performance, significantly facilitating engineering and management decisions on the application of costly horizontal well technology.

1. Introduction

In gas condensate reservoirs, as the pressure falls below the dew point pressure, a bank of condensate forms around the wellbore which affects the flow behaviour and consequently well productivity. Under such conditions, two hydrocarbon phases (gas and condensate) co-exit making the phase and flow behaviour completely different from those of dry gas reservoirs. It is also well documented that the fluid flow behaviour around the wellbore region, of near critical gas condensate systems, characterized by very low interfacial tension, is different from that of conventional oil gas systems. Thus, the relative permeability of gas condensate systems has a unique dependency on interfacial tension [3] and velocity [5], Henderson et al. 1996, [1]. Accordingly, any reservoir simulator or model proposed for well calculations in such systems must take into account these effects in order to make a sufficiently accurate prediction of the well performance.

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Nomenclature

a	extension of drainage volume of horizontal well in x direction
a_i	coefficients of the equation
B_o	oil formation factor
h	reservoir thickness
I_{ani}	$\sqrt{\frac{k_h}{k_v}}$
J	productivity index
k	absolute reservoir permeability
k_d	permeability after porosity blockage
k_v	vertical permeability
k_h	horizontal permeability
k_r	relative permeability
K_{max}	end point of the Corey relative permeability curve
L	length
$\dot{m}$	mass flow rate
P	pressure
P_c	capillary pressure
P_d	threshold pressure
q	flow rate
r	radius
r'_w	effective wellbore radius
Re	Reynolds
S	skin factor
S_d	damage skin factor
S_f	flow skin factor
S_m	geometric skin factor
S_θ	pseudo skin factor
S_z	horizontal well location skin
V	*velocity*
x_{ic}	scaled coded parameters
x_j	mass fraction of component j in liquid phase
X_{res}	*length of the reservoir*
y_j	mass fraction of component j in vapour phase
Y_{res}	*width of the reservoir*
z	z direction
z_j	mass fraction of component j in the mixture of liquid and vapour

Greek Letters

ϕ	undamaged porosity
μ	viscosity
M	mobility
ρ	density
β	inertia factor
Ψ	pseudo pressure
θ	deviation angle
λ	pore size distribution index
∇	Laplace operator
σ	interfacial tension
ν	flow rate

Subscript

ave	average
bhp	bottom hole pressure
c	condensat
d	damage
dew	Dew point
Darcy	Darcy flow
DW	deviated well
e	external as in r_e.
eqphase	Equivalent phase
g	gas
HW	horizontal well
i	an index
j	an index
o	oil
OH	open-hole
pp	partial penetrating
x	x-direction
y	y-direction
w	refers to well-bore

Abbreviations

AD%	absolute deviation (percentage)
AAD%	average absolute deviation (percentage)
C1	methane
n-C4	normal butane
n-C10	normal decane
CCD	central composite design
CCE	constant composition expansion
CVD	constant volume depletion
1-D	one dimensional
2D	two dimensional
3-D	three dimensional
DW	deviated well
EOH	equivalent open-hole
EOS	equation of state
GTR	gas total ratio (in flow)
HW	horizontal well
IFT	interfacial tension
k_{rgtr}	relative permeability ratio
LRM	linear response surface model
PR	productivity ratio
PR3	3 parameter peng robinson equation of state
PSS	pseudo-steady state
SEE	standard error of estimate
SS	steady state
IFT	interfacial tension
$\overline{M}$	mass mobility ratio
PDE	partial differential equation
VW	vertical well

The reduction of relative permeability at high velocities due to negative inertia (non-Darcy flow) was first introduced by Forchhiemer [11,12]. The dependency of the relative permeability of low IFT systems on interfacial tension was first reported by Bardon (1980). The improvement of the relative permeability of gas and condensate fluids due to an increase in velocity was first reported experimentally by the gas condensate recovery research team of Heriot-Watt University (Danesh et al. [5], Henderson et al. (1996)). The positive coupling effect, which refers to the improvement of relative permeability as velocity increases and/or IFT decreases, has been shown theoretically and experimentally to be due to the simultaneous coupled flow of the gas and condensate phases with intermittent opening and closure of the gas passages by the condensate at the pore level (Jamiolahmady et al. [22]).

The breakthrough of drilling technology in developing and completing horizontal wells has significantly impacted oil and gas reservoir development strategies. Such a well trajectory increases the well exposure to the reservoir drainage area and thereby appreciably increases the well productivity. However, the cost of horizontal wells is often a major barrier. Over the last few years, since horizontal wells have been