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Application of a mathematical method in calculation of the skin variation during a real field acidizing operation

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HIGHLIGHTS

- A new mathematical approach for estimation of well output rate based on CRM equations.
- Using optimization for estimation of acid reaction rate in the near wellbore region.
- Investigation of acid reaction rate as a main parameter of acidizing operation.
- A new skin variation estimation procedure during field acidizing operations.

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ABSTRACT

The efficiency of an acidizing operation is usually assessed through ordinary well testing methods. These methods are performed only after the acidizing operation, and it is difficult to monitor and evaluate real-time efficiency of acidizing operation. Understanding the performance of the acidizing during the service, by analysis of the acidizing data is a viable approach to this costly and challenging process. The estimation of the skin changes needs an appropriate mathematical method that can handle the main aspects of an acidizing operation. It is tedious to model a real acidizing operation due to the heterogeneity of the reservoir, an unknown reaction rate of acid in reservoir condition, unwanted fluid loss, opening and closing of the wing valve, etc. In this paper, we have presented a new well testing method for calculating the skin variations of open hole vertically drilled carbonate reservoir during an acidizing operation, by using history matching of the surface pressure data. The proposed method is based on continuity equations of acid in the reservoir coupled with analytical equations of ORPM (Output Rate Prediction Method) in the wellbore. The novelty of the proposed method is using a new mass transfer coefficient in continuity equations of acid, and a mathematical approach (ORPM) for the appropriate estimation of bottomhole acid injection rate and fluid loss, that lead to a proper evaluation of the skin variation during a field acidizing operation.

1. Introduction

The main purpose of well testing is the proper calculation of the average permeability and the skin of the reservoir. In a regular well testing data analysis, it is assumed that the permeability and the skin of reservoir remain constant during the injection or production. But in an acidizing operation in which a reactive fluid is injected into the porous medium, the permeability and the skin of reservoir are changing continually.

In acidizing, the reaction regimes are classified into two types of reaction controlled and mass transfer controlled (Panga et al., 2005; Safari et al., 2016). In the reaction controlled regime, the surface reaction rate is too smaller than the mass transfer rate of reactants, making the surface reaction rate determinative in the speed of consumption of the reactants. In the mass transferred reaction regime, like the reaction of hydrogen ions with carbonate rock, the surface reaction rate is much higher than the mass transfer rate of reactants to the surface, and the hydrogen ions are consumed as soon as they arrive at the surface of the carbonate rock.

The high reaction rate of hydrogen ions with carbonate rock causes a competition between convection rate and reaction rate (Panga et al., 2005). When the convection rate is too slow, no hydrogen ion arrives at the deep interval pores of the rock. These ions only react with the face of the rock, making the face of rock dissolved (Panga et al., 2005; Kalia and Balakotaiah, 2009; Tabasy

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Nomenclature

List of symbols

a_{v0}	initial average interfacial area per unit volume of the medium (m^{-1})
a_v	interfacial area per unit volume of the medium (m^{-1})
C_f	concentration of acid in the fluid ($\frac{mole}{L}$)
C_s	concentration of acid at the solid–fluid interface ($\frac{mole}{L}$)
C	compressibility of injected fluid ($\frac{1}{Pa}$)
D_m	molecular diffusivity ($\frac{m^2}{sec}$)
D_e	effective dispersion ($\frac{m^2}{sec}$)
d	Wellbore diameter (m)
f	friction factor
fi	fraction of the inlet rate that is directed toward the outlet rate in CRM
i	surface injection rate ($\frac{m^3}{sec}$)
J_C	connectivity index of the wellbore ($\frac{m^3}{sec\ Pa}$)
K	permeability of the medium (m^2)
K_0	initial average permeability of the medium (m^2)
k_c	mass transfer coefficient ($\frac{m}{sec}$)
P	pressure (Pa)
$\overline{P}$	average pressure of a pipe without considering the effect of gravity (Pa)
P	output pressure of a pipe without considering the effect of gravity (Pa)
q	bottomhole flow rate ($\frac{m^3}{sec}$)
r_p	pore radius (m)
r_{p0}	initial average pore radius (m)
Re	Reynold's number
t'	time (sec)
U	magnitude of the Darcy velocity ($\frac{m}{sec}$)
V_{well}	Wellbore volume (m^3)
V	fluid velocity in the wellbore ($\frac{m}{sec}$)
v	kinetic viscosity of the fluid ($\frac{m^2}{sec}$)
α	dissolving power of acid, defined as grams of solid dissolved ($CaCO_3$) per mole of HCl ($\frac{gr}{mole}$)
λ	numerical coefficient that depend on the structure of the medium
α_s	numerical coefficient dependent on the structure of the medium
β	exponent (from Carmen-Kozeny relation: $\beta = 2$)
φ	porosity of the medium
φ_0	initial average porosity of the medium
μ	viscosity of the injected liquid (cP)
ρ_f	density of fluid ($\frac{gr}{L}$)
ρ_s	density of $CaCO_3$ ($\frac{gr}{L}$)
Ψ	compressibility constant
Ω_1	matching parameter (mass transfer coefficients)
Ω_2	matching parameter (mass transfer coefficient reduction factor)
ε	pipe roughness (m)
τ	time constant

and Rashidi, 2015; Liu et al., 2016, 2017). This type of dissolution pattern is called the face dissolution. When the convection rate is too high, many hydrogen ions pervade the internal pores of the rock. In this condition, these pores react with hydrogen ions partially. Such dissolution pattern is called the uniform dissolution. Between these two manners, there is an optimum rate which hydrogen ions do not stop in the face of the rock and do not permeate in the many interval pores. At such a rate, a very conductive channel is made through the rock which is called wormhole. These channels penetrate deeply into the formation and facilitate the flow of oil and gas (Panga et al., 2005; Kalia and Balakotaiah, 2007; Cohen et al., 2008; Liu et al., 2016, 2017). In Fig. 1 different types of dissolution in a core have been shown.

Many researchers have tried to simulate acidizing analytically and numerically (Daccord et al., 1989; Golfier et al., 2002; Panga et al., 2005; Kalia and Balakotaiah, 2007, 2009; Maheshwari and Balakotaiah, 2013; Ghommem et al., 2015; Liu et al., 2016, 2017; Wei et al., 2017). Enormous efforts have been made for simulation of wormhole creation and propagation, including cylindrical models, pore network models, quantitative models, and models based on continuum equations. In the cylindrical models, it is assumed that the shape of a wormhole is always like a cylinder, so these models are not appropriate for the description of different types of the dissolution patterns (Wang et al., 1993; Buijse, 1997; Huang et al., 1997, 1999). Several authors have tried to simulate acidizing by pore network modeling (Hoefner and Fogler, 1988; Daccord et al., 1989; Fredd and Fogler, 1998). A pore network modeling is not appropriate for the pore merging (Golfier et al., 2002). Quantitative models have a good agreement with experimental data (Hoefner and Fogler, 1988; Daccord et al., 1993; Fredd and Fogler, 1998). Models based on the continuum equations talk about the continuity equations of fluid and acid. These models started by Liu et al., 1997, developed by Golfier (2002) and Panga (2004 & 2005) and still are used by many researchers for acidizing simulation (Kalia and Balakotaiah, 2007; Cohen et al., 2008; Kalia and Balakotaiah, 2009; Maheshwari and Balakotaiah, 2013; Ghommem et al., 2015; Liu et al., 2016, 2017; Wei et al., 2017). In this model, the equations come from two different scales of Darcy scale and pore scale; then these equations are coupled and solved numerically or analytically (Panga et al., 2004, 2005).

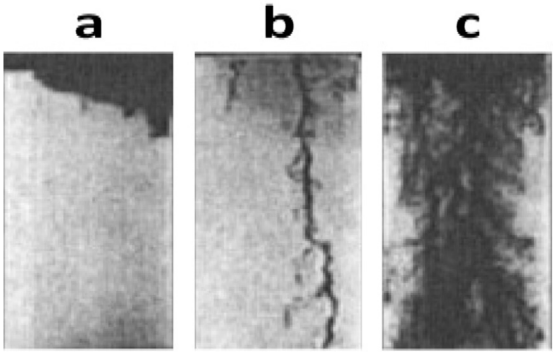

Fig. 1. Different types of dissolution resulting from different injection rate (Fredd and Fogler, 1999). (a) Face dissolution Q = 0.04 cc/min, (b) Wormhole Q = 1.05 cc/min, (c) Uniform dissolution Q = 60 cc/min.

Most of the acidizing simulations have been done in the core scale, and just a few of the researchers have tried to simulate a real field acidizing case (Tardy et al., 2007; Ghommem and Brady, 2016). Tardy (2007) studied the effect of self-diverting acid in a gas reservoir, and Ghommen (2016) applied Tardy's quantitative wormhole propagation radius in a synthetic field acidizing case.

As all of these researchers have stated, the fluid injection rate and the reaction rate of the acid are the most important parameters that determine the type of dissolution pattern. This type of dissolution pattern directly impacts the pressure response of the porous medium when exposed to a certain injection rate. Hence, both of these parameters must be estimated as precise as possible. In this paper, we firstly present a new mass transfer coefficient for