Prediction of Elemental Sulphur Saturation around the Wellbore

GJRE Classi ca on (FOR)
C 090403, 090499, 090499, 090406

Fadairo Adesina[1], Ako Churchill[2]

***Abstract*- Sour gas reservoirs with high content of hydrogen sulfide are distributed widely around the world. Solid elemental sulfur which dissolves in the gas phase originally in the reservoir in form of sulphur compound, may deposit when the thermodynamic conditions of the temperature, pressure or composition changes in the process of production. Deposition of solid elemental sulfur may block the pores in the formation and significantly affect the gas deliverability.**

Robert Bruce model has been exploited to describe the phenomenon of elemental suphur induced flow impairment and the key factors that influence the magnitude around the well bore region. Previous model assumed constant porosity damage factor, which is the function of variable parameters that govern magnitude of flow impairment induced by elemental suphur.

This study presented an improved analytical model for predicting elemental sulphur build up rate around the well bore. Results show that the previous model under-estimated elemental sulphur build up rate at different radial distance around the wellbore while the minimum blockage time was over-estimated.

I. Introduction

Sulphur compounds are considered as the most hazardous non-hydrocarbons in reservoir fluids, because of their corrosive nature, their deleterious effects of petroleum products, their tendency to plug porous medium which may impair formation productivity, their effect on oxidation characteristics, and their disagreeable odor.

Studies have shown that almost all deep sour reservoirs precipitate elemental sulphur either occurring as a result of decomposition of H_2S to give elemental sulphur or occurring as indigenous usually referred to as native sulphur as a dissolved species. Precipitation of this native (elemental) sulphur occurs as a result of thermodynamic changes in the reservoir during production. Elemental sulphur is often present in sour gases and/or crude oils in appreciable quantities at reservoir condition. Variation in reservoir condition of pressure and temperature that occurs below sulphur saturated state causes sulphur deposition.

Precipitation and deposition of elemental sulphur within reservoirs, in the near-wellbore area may significantly reduce the inflow performance of sour-gas wells and thus affect economic feasibility negatively[4]. Formation damage which is the inevitable end effect of the precipitation of elemental sulphur is defined as obstructions occurring in the Near-wellbore region of the rock matrix primarily as a result of permeability reduction. Many of the operational and reservoir parameters influence sulphur deposition have been identified by Hyne[9-11].

Most of the reported investigations related to sulphur deposition have focused on deposition in the well, while few studies have been reported on the effect of deposition within the formation. Among other investigators, Kuo (1966)[2] investigated the effect of the deposition of immobile elemental sulphur from a homogeneous reservoir within a fluid containing 78% H_2S and an estimated sulphur content of $120g/m^3$. Field results have also been reported by Chernik and Williams (1993)[13] for the effect of mobile liquid sulphur deposit on the productivity of the high H_2S (>90%) content Bearberry (Alberta, Canada) sour gas reservoir. Bruce E. Roberts (1997)[1] focused on a more conventional sour gas reservoir with H_2S concentrations less than 25% and equilibrium sulphur content of the reservoir fluid at these concentrations of H_2S generally less than $2g/m^3$. Investigation carried out by Shedid A. Shedid and Zekri Y. Abdulrazag (2002)[15] presented an experimental approach on elemental sulphur deposition in carbonate oil reservoirs with results that showed the influences of oil flow rate, initial sulphur concentration of crude oil, and reservoir rock permeability on elemental sulphur plugging in carbonate oil reservoirs.

This paper presents an improved model of Robert Bruce (1997) formulation on elemental sulphur saturation at different radial distance away from the well bore. His formulation was modified by incorporating effect of porosity damage function which was overlooked his model.

II. Model Formulation

The following assumptions will be made use of so as to enable simplicity in developing a simple analytical model:

Viscosity is assumed constant.

Gas formation volume factor is assumed constant.

Sulphur concentration (or solubility) change with pressure is considered to be constant.

Initial condition for sulphur saturation is assumed zero i.e. $S_s=0$ @ $t=0$.

A. *Developing The Analytical Model*

Considering the radial flow of gas at constant rate q saturated with solid state particles at a location r from the wellbore. Assuming the semi-steady state flow equation a pressure gradient due to pressure of solid in the flow path can be expressed as

Author[1]-Department of Petroleum Engineering, Covenant University Ota Nigeria, (email-adesinafadairo@yahoo.co)
Author[2]-(e-mail-akochurchill@yahoo.com)

$$\frac{dp}{dr} = \frac{qB\mu}{2\pi rhk_a k_{r_g}} \qquad (1)$$

The fractional change in volume of solid, dv_s which drops out and gets deposited in the volume element over the time interval dt is given as

$$dv_s = q.\left(\frac{dc}{dp}\right)_T dp.dt \qquad (2)$$

The deposit occupies a fractional bulk volume dS_s in the porous media over an infinitesimally small radial distance increment dr, given by

$$dS_s = \frac{dV_s}{2\pi rhdr\phi_i(1 - Sw_i)} \qquad (3)$$

The change in the volume of deposited sulphur as a fraction of the hydrocarbon pore volume,dS_s over this time interval is given as

$$dS_s = \frac{q.\left(\frac{dc}{dp}\right)_T .\boldsymbol{dpdt}}{2\pi rh.\boldsymbol{dr}.\phi_i(1 - Sw_i)} \qquad (4)$$

Incorporating equation (1) into equation (4), we have:

$$dS_s = \frac{q^2\left(\frac{dc}{dp}\right)_T B\mu dt}{4\pi^2 k_a k_r h^2.\phi_i(1 - Sw_i)r^2} \qquad (5)$$

Introducing Kuo (1972) correlation on relative permeability and solid (elemental sulphur) build-up/saturation to account for effect of elemental sulphur in the flow path on effective permeability damage function

$$k_r = exp(aS_s) \qquad (6)$$

Also correcting for porosity damage function due to precipitation of elemental sulphur by incorporating the above relative permeability function given by Kuo (1972)2 into the permeability-porosity relationship given by Civan et al (1989)12 and derive a relationship between initial porosity ϕ_o, instantaneous porosity ϕ_i and the elemental sulphur saturation.

$$\frac{k_{g_i}}{k_{g_o}} = \left(\frac{\phi_i}{\phi_o}\right)^3 \qquad (7)$$

As stated above using the relative permeability function

$k_r = exp(aS_s)$ (8)

Assuming the initial condition for elemental sulphur saturation is zero i.e. Ss=0 @ t=0 k=k_{g_o}

$$\frac{k_{g_i}}{k_{g_o}} = \frac{k_a k_{r_i}}{k_a k_{r_o}} = exp(aS_s) = \left(\frac{\phi_i}{\phi_o}\right)^3 \qquad (9)$$

Taking the above assumptions into consideration equation (9) gives

$$exp(aS_s) = \left(\frac{\phi_i}{\phi_o}\right)^3 \qquad (10)$$

Solving equation (10) , we have:

$$\phi_i = \phi_o e^{\left(\frac{aS_s}{3}\right)} \qquad (11)$$

Substituting equation (11) into equation (5) and solve; we have:

$$\frac{dS_s}{dt} = \frac{q^2\left(\frac{dc}{dp}\right)_T B\mu}{4\pi^2 k_a h^2.\phi_o e^{\left(\frac{4aS_s}{3}\right)}(1 - Sw_i)r^2} \qquad (12)$$

Eqn. 12 can be integrated subject to the initial condition that Ss=0 at t=0.

$$\int_0^{S_s} 4\pi^2 k_a h^2 r^2.\phi_o(1 - Sw_i)e^{\left(\frac{4aS_s}{3}\right)} dS_s = \int_0^t q^2\left(\frac{dc}{dp}\right)_T B\mu\, dt \qquad (13)$$

Making S_s the subject gives the equation that models the sulphur build – up in a reservoir at different radial distances and at given times via precipitation.

$$S_s = \frac{3}{4a} ln\left[\left(\frac{aq^2B\mu\left(\frac{dc}{dp}\right)_T t}{3\pi^2 r^2 h^2 k_a \phi_o(1 - S_{wi})}\right) + 1\right] \qquad (14)$$

III. Model Validation

Using the same data provided by Robert E. Bruce in his paper, the sulphur content of bottom-hole sample obtained before production and as determined with fluid and reservoir fluid properties for this field case is given below and is used as base-case properties for the evaluation. Table 1 and 2 show the reservoir fluid properties for this field case and data for model parameters.

Table 1: Reservoir base case properties

Reservoir temperature	81°C
Outer radius, m	1500
Effective wellbore radius @ s=-2, m	0.74
Pay thickness, m	26
Initial pressure, kPa	36600
Porosity (fraction)	0.04
Absolute permeability, md	0.7
Gas relative permeability, k_r	$e^{(-6.22*Ss)}$
BHP constraint, kPa	10000

Table 2: Analytical Model parameters

B	0.004583
μ, Pa.s	0.0000228
k_a	0.7
h, m	26
S_{wi}	0
dc/dp, m³/m³.Pa	$4*10^{-15}$
a	-6.22
ϕ	0.04

IV. Discussion of Results

Comparison and analysis of the results from developed model and Robert E. Bruce model shows slightly-considerable difference in the time of elemental sulphur build-up and invariably the time for complete blockage at difference radial distances from the wellbore. The results obtained from the modified model have shown that pore passage blocks faster at difference radial distances away from the wellbore compare with Robert E. Bruce model. This implied that the Robert E. Bruce model might had under-estimated elemental sulphur build up rate at different radial distance around the wellbore while the minimum blockage time might had over-estimated as report in fig 1. The results calculated for the elemental sulphur saturation and minimum blockage time at different radial distance around the wellbore, using both modified and Robert E. Bruce models respectively have been shown in table 3:

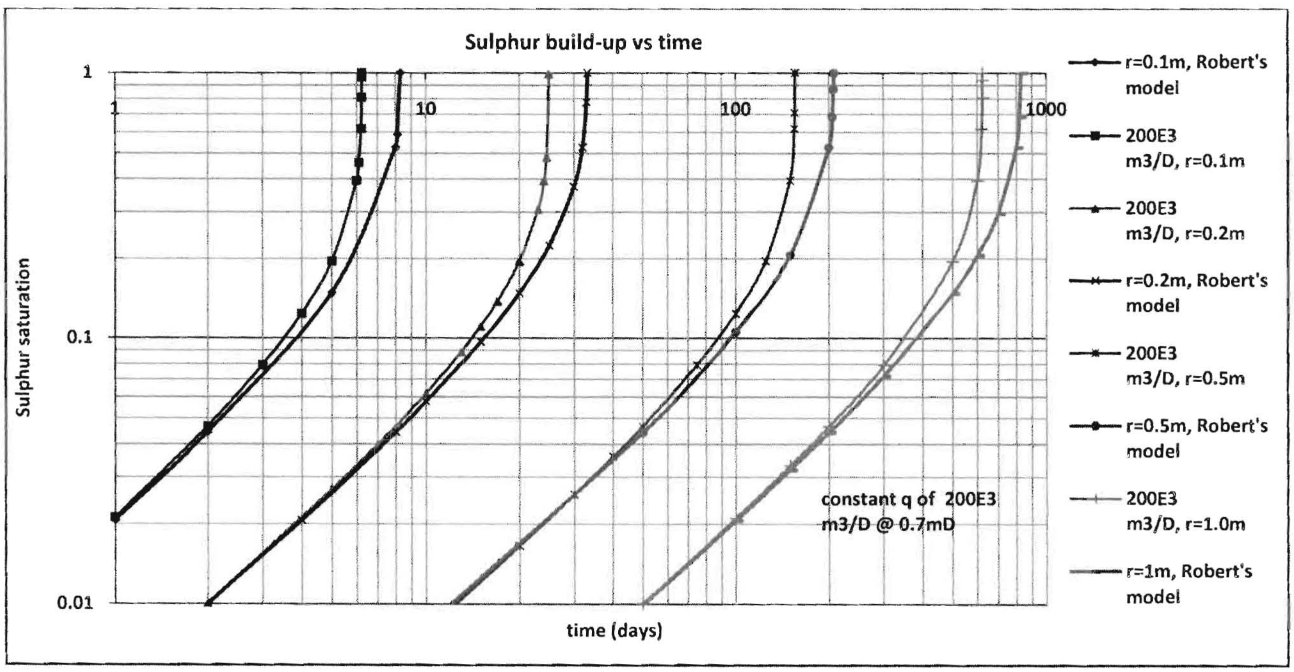

Fig .1 Comparison of analytical model developed in this project and that developed by Robert E. Bruce to predict sulphur deposition as a function of radial distance

	Robert's model		Our model	
r=0.1m	**t(days)**	**S_s**	**t(days)**	**S_s**
	1	0.020595608	1	0.021069017
	2	0.04422271	2	0.046615645
	5	0.147794086	3	0.079071279
	8	0.525369377	4	0.123616656
	8.1	0.586352068	5	0.195027387
	8.3	**0.997643987**	6	0.394027033
			6.1	0.459894922
			6.2	0.616347771
			6.23	0.809246428
			6.236	0.964699858
			6.24	**0.997646681**
r=0.2m	**t(days)**	**S_s**	**t(days)**	**S_s**
	1	0.004906871	1	0.004932261
	4	0.020595608	2	0.010074913
	8	0.04422271	5	0.02696636
	10	0.057480367	7	0.039703939
	15	0.096377166	10	0.061754751
	20	0.147794086	13	0.088761249
	25	0.223839273	15	0.110845564
	30	0.373095085	17	0.137902404
	32	0.525369377	20	0.195027387
	33	0.775643507	23	0.307339857
	33.2	**0.997643987**	24	0.394027033
			24.5	0.484073776
			24.94	**0.992093409**
r=0.5m	t(days)	S_s	t(days)	S_s
	1	0.000775105	1	0.000775729
	50	0.04422271	10	0.007991459
	100	0.105428372	20	0.016550391
	150	0.205481393	30	0.025763591
	200	0.525369377	40	0.035739427
	205	0.685798718	50	0.046615645
	207	0.871519281	75	0.079071279
	207.5	**0.9976439868**	100	0.123616656
			125	0.195027387
			150	0.394027033
			155	0.616347771
			155.5	0.707911565
			155.9	**0.997646681**
r=1m	**t(days)**	**S_s**	**t(days)**	**S_s**
	1	0.000193426	1	0.000193465
	50	0.00996823	50	0.010074913
	100	0.020595608	100	0.021069017
	150	0.031975518	150	0.033167033
	200	0.04422271	200	0.046615645
	300	0.071930343	300	0.079071279
	500	0.147794086	500	0.195027387
	600	0.205481393	600	0.394027033
	700	0.296315186	620	0.616347771
	800	0.525369377	623	0.809246428
	820	0.685798718	623.5	0.938850602
	830	**0.997643987**	**623.6**	**0.997646681**

Table 3- Comparison between the analytical model developed and Robert's mod

A Effect of Permeability on Sulphur build-up in the formation

Flowing gas at constant rate of 200E3 m^3/D and varying permeability (0.7md, 3.5md, 7.0md), and observing the sulphur precipitation and eventual plugging with respect to time at similar radial distances from the wellbore. The plot of elemental sulphur saturation against production time has shown in fig 2, that deposition of sulphur occurs faster in formations with lower permeability. The high permeability reservoir experiences the lower the pressure gradient and likewise the less significant the deposition of sulphur in such reservoir compare with tight gas reservoir.

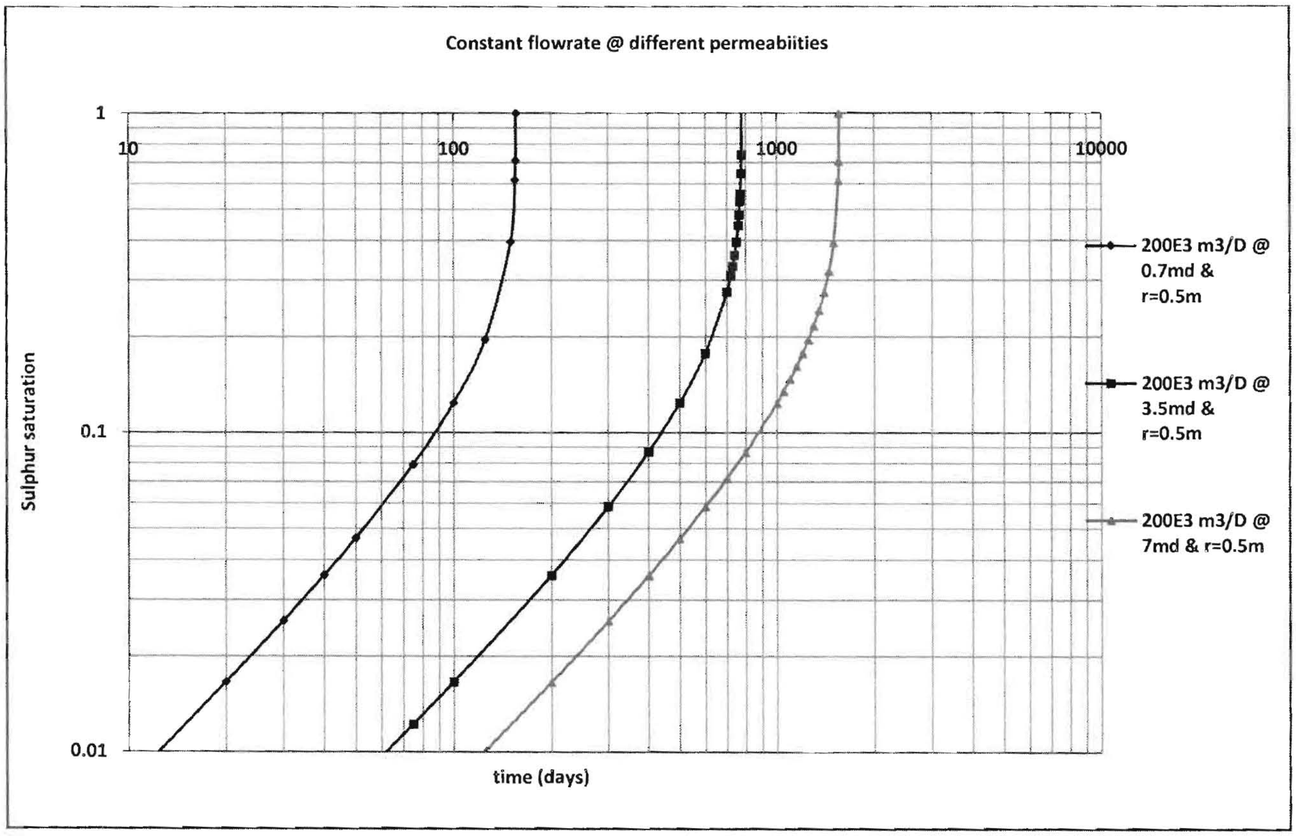

Fig. 2 Effect of permeability on deposition of elemental sulphur (at a radial distance of *0.5m* and at a rate of *200E3 m^3/D*)

B. Effect of Flow rate on Sulphur build-up in the formation

The effect of flow rate on sulphur deposition was investigated by varying gas flow rates at constant permeability using the modified model. In figure 3, it was noticed that saturation of sulphur at all radial distances of consideration in the formation was accelerated by increasing flow rates. The effect of variable flow rate on sulphur deposition will be made more vivid in a more permeable formation and for this reason the permeability used in this investigation was times 10 of the original formation permeability. As the gas flow rate is increased there is a proportional increase in pressure drawdown (in obedience to Darcy's law) which brings about deposition of elemental sulphur away the well bore region.

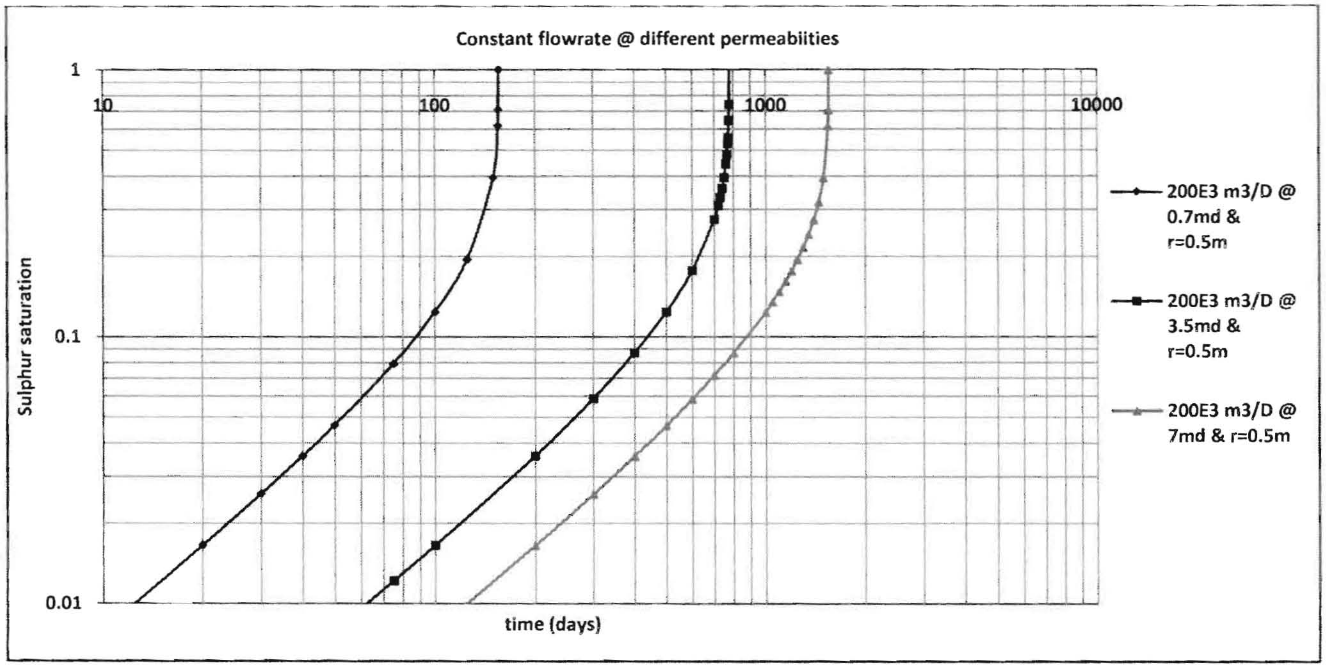

Fig. 3. Effect of permeability on deposition of elemental sulphur (at a radial distance of *0.5m* and at a rate of *200E3 m^3/D*)

V. CONCLUSION

The following conclusions were drawn from the result of this study Previous model opined by Robert Bruce might had under-estimated elemental sulphur build up rate at different radial distance around the wellbore while the minimum blockage time might had over-estimated. Sulphur deposition in the formation is a near-wellbore process occurring generally within the distance range of 0.0m to 2.0m away from the well bore. Reducing the flow rate will generally increase the production time of a well before significant flow impairment by deposition of sulphur. Whether reducing the flow rate will increase the cumulative production before plugging depends on the sulphur-solubility with pressure. Also, to slow down deposition in the formation, well-stimulation techniques such as acid treatment can be carried to increase the near-wellbore permeability and this as a matter of consequence will reduce the pressure gradient which will decelerate the deposition process.

VI. NOMENCLATURE

a	Empirical constant
B	Formation Volume factor, m^3/stm^3
c	Concentration of sulphur in gas, m^3/m^3
$\frac{dc}{dp}$	Solubility change per unit pressure, m^3/m^3-Pa
h	Net pay thickness, m
K_a	Absolute permeability at initial water saturation, m^2
k_r	Gas relative permeability, m^2
q	Gas flow rate, m^3
r	Radial distance from well, m
S_s	Sulphur saturation relative to hydrocarbon Pore volume
t	Time (days)
V_s	Volume of deposited sulphur, m^3
ϕ	Instantaneous porosity
ϕ_i	Initial porosity
μ	Viscosity, Pa.s

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