ARTICLE IN PRESS

Journal of Petroleum Science and Engineering (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

A new model for predicting critical gas rate in horizontal and deviated wells

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ARTICLE INFO

Keywords:
Critical rate
Critical velocity
Liquid loading
Horizontal wells
Deviated wells
DLS
Dogleg severity
BUR
Buildup rate
Lifting from the curve
KOP
Kickoff point
Gas wells
High GLR wells
Low GLR wells
Liquid rich wells
Gas liquid ratio

ABSTRACT

The author's intent through this work is to shed light on the current methods of predicting the onsets of liquid loading and to clarify that there is a difference in critical gas rate predictions between horizontal and vertical wells.

Results using 67 wells from literature show that the new model is capable of predicting the critical gas flow rates in horizontal wells within 15.8% of the actual values, 6% improvement over the currently available horizontal well models, and 8–21% improvement over the currently available vertical well models. Experimental results from two horizontal wells tend to support the finding from literature comparison. The new model accounts for the effect of geometry on flow especially particle impact with the flow conduit wall as a result of change in geometry present in horizontal wells. When this effect is accounted for, as in the new model, the estimation of the critical gas rate is more accurate and yields optimized production performance from horizontal wells. The new model yields best results for gas rates less than 10,000 Mscf/d and for buildup rates between 3 and 30°/100 ft.

1. Introduction

Initially a multiphase flow gas dominated well has sufficient energy to flow naturally. Wallis (1969) stated that at very high velocities the liquid film thickness approaches zero and all liquids are entrained in the gas stream, and as the gas velocity decreases, fluids accumulate to form a thicker film surrounding a gas core with entrained droplets. As production continues, the well continues to deplete and lacks the energy to move the liquids, which in turn allows most or all entrained liquid droplets to fall and accumulate. The latter causes the buildup of a hydrostatic column above the producing interval leading the well to flow at a lesser capacity rate or load up and eventually cease flowing. Multiple drawbacks are associated with wells flowing below the critical rate. These drawbacks include, but not limited to, loss of production, change of relative permeability, scale deposit, casing damage. Therefore, it is important to correctly predict when the well critical rate is going to occur so that appropriate actions can be taken.

Since the vertical models do not accurately predict the critical rate, usually under-predict it, it is suspected that the change in geometry in horizontal wells causes an effect that is not accounted for by the vertical models. The hypothesis is that the droplets entrained in the gas stream impact the wall of the flow conduit due to continuous change in the build rate throughout the curved section which causes the droplets to lose a fraction of their energy. If the hypothesis is true, then there should be an increase in the required velocity to keep the droplets from falling and accumulating in the wellbore. Accounting for this effect will yield better prediction of the critical gas rate.

2. Literature review

Turner et al. (1969) pioneered the effort of understanding the causes of liquid loading. They pursued both a film model and a droplet model and concluded that the film model was not adequate since it did not fit their data. However, the droplet model, when compared to 106 wells in their data set showed a good fit but only after adjusting it by a factor of approximately 20%.

The theoretical work lies mainly on the required velocity of the streaming gas to offset the terminal velocity of a spherical liquid droplet with a diameter (d_p). That velocity where the droplet stops falling and remain at rest is called the critical velocity below which the droplet would settle further and above which the droplet will start moving upward.

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http://dx.doi.org/10.1016/j.petrol.2016.11.038
Received 20 June 2016; Received in revised form 23 October 2016; Accepted 30 November 2016

Nomenclature

A	conduit cross sectional area, ft^2
BFPD	barrels of fluid per day
B_g	gas formation volume factor
BOPD	barrels of oil per day
BUR	build up rate, °/100 ft
C_d	drag coefficient, dimensionless
DLS	dogleg severity, °/100 ft
d	flow conduit diameter, in.
d_p	droplet diameter, in.
FTP	flowing tubing pressure, psia
BHFP	Bottomhole Flowing Pressure, psia
$F_{d,\ after}$	drag force on particle after impact
$F_{d,\ before}$	drag force on particle prior to impact
$F_{d,\ mup}$	difference in drag before and after impact
g	acceleration of gravity 32.17 ft/sec^2, or 9.8 m/sec^2
g_c	gravitational conversion factor 32.17 lbm-ft/lbf-sec^2
GOR	gas oil ratio, scf/bbl
N_{Rep}	particle Reynolds number, dimensionless
P	pressure at the evaluation point, psia
q_c	critical gas rate, Mscf/d
q_o	oil rate, BOPD
q_w	water rate, BWPD
T	temperature at the evaluation point, °R
TR	Turner Ratio, dimensionless
V_b	particle restitution velocity, ft/s
V_c	critical velocity as expressed by Turner's derivation, ft/s
V_{eff}	effective lift velocity, ft/s
V_i	particle Initial velocity, ft/s
V_{mup}	additional velocity above the critical velocity necessary to maintain the critical condition post rebound, ft/s
We	Webber number, dimensionless
Z	gas compressibility factor

Greek symbols

α	restitution velocity factor
β	effective velocity factor
ρ_l	liquid density, lbm/ft^3
ρ_m	mixture density, lbm/ft^3
ρ_g	gas density, lbm/ft^3
σ	surface tension, dynes/cm
θ_i	incidence angle in degrees
θ_b	the rebound angle in degrees
γ_g	gas specific gravity
ω	inclination angle from the Belfroid model

The resulting equation, using the critical Webber number, We, of 60 and the drag coefficient, C_d, of 0.44, is referred to as the Turner critical velocity equation. The Coleman version uses We of 30 and can be written in oil field units as:

$$V_c=1.593\left(\frac{\left(\rho_l-\rho_g\right)}{\rho_g^{\,2}}\sigma\right)^{\frac{1}{4}} \tag{1}$$

Coleman et al. (1991a, 1991b, 1991c) presented series of papers discussing liquid loading onsets for low pressure wells. They compared the Turner equation to all 56 wells in their data set and concluded that the 20% adjustment suggested by Turner is not necessary for low pressure wells, i.e. less than 500 psi.

Multiple variations of the original Turner equation have been proposed based on different droplet shape and flow regime. Nevertheless, the overall physical model remained the same.

Belfroid et al. (2008) cited that steady state models, like Turner, underestimate the critical rates of gas wells. They discussed the effects of hole inclination, flow regime transition, and the interaction between the tubing outflow and reservoir performance on liquid loading. They concluded that high permeability wells do not respond well to dynamic disturbances and may require twice the turner criterion, while low permeability wells seem to cope better with dynamic conditions.

As far as the influence of the inclination angle, Belfroid et al. stated that there is a diminished influence of gravity as the well moves toward a horizontal geometry. They stated that for a horizontal well, no liquid loading can occur because of the absence of forces on the liquid that can counter the flow of gas. It was also mentioned that the change from horizontally stratified flow to vertically distributed flow driven by inclination allows for the liquid film to be progressively thicker at the bottom compared to the top of the tube. Therefore, both the diminishing effects of gravity and the film thickening affect the critical rate such that the latter increases with a medium inclination as a proxy to increased film thickness, while the lower effect of gravity is sensed at higher inclinations. The maximum required rate is identified to occur at 50 degree inclination, where, the critical velocity required is 40% higher than that predicted by vertical models.

In order to incorporate the inclination dependency, Belfroid et al. turned to the Fiedler shape function from flooding experiments (Fiedler, 2004) because it captures the inclination dependence. They concluded that a modified Turner model that is merged with the Fiedler shape function would be better at predicting the critical gas rates in deviated wells. The resulting equation which includes the inclination angles ω is as follows:

$$V_c=1.593\left(\frac{\left(\rho_l-\rho_g\right)}{\rho_g^{\,2}}\sigma\right)^{\frac{1}{4}}\frac{\left(\sin(1.7\omega)\right)^{0.38}}{0.78} \tag{2}$$

Veeken et al. (2009) investigated the influence of reservoir parameter and well parameters on the critical gas rate. They found that the strongest correlation exists between the Turner Ratio (TR), which is the ratio of actual to predicted gas critical rate, and observed critical gas rate (q_c) using a quadratic fitting. They then suggested a new form to identify the critical gas rate as function of the turner calculated critical gas rate such as:

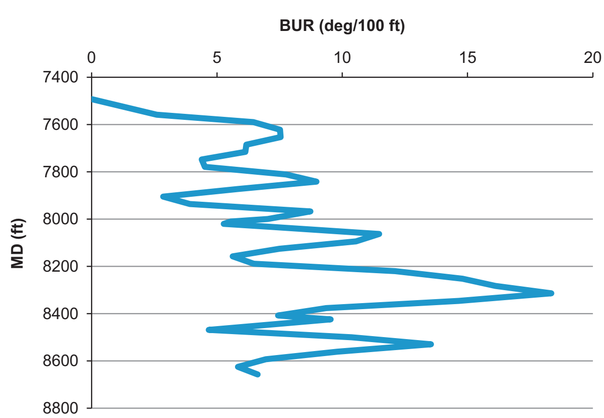

Fig. 1. Change of BUR versus MD in horizontal and deviated wells.