Challenging Conventional Erosional Velocity Limitations for High Rate Gas Wells

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Abstract

For prolific gas reservoirs, Big Bore gas wells can allow operators to increase production rates. Currently, few Big Bore gas wells operate worldwide with limited information available on the effect of increased extraction rates. Consequently operators require an improved understanding on the significance of increased extraction rates on erosion. The American Petroleum Institute's Recommended Practice 14E (API RP 14E) provides a method for determining the threshold erosion velocity for gas wells, however API RP14E has been found to be conservative in predicting the erosional velocity in sand laden fluids. Some of the highest velocities within the production string are experienced through the subsurface safety valve (SSSV). Understanding erosion in the vicinity of the SSSV is important as its failure is both expensive and complex.

This project will provide the information to determine the maximum allowable extraction rate within a Big Bore well. The flow of gas and sand through a typical 7 inch SSSV has been modelled using computational fluid dynamics. The erosion rate density is found to be highest at the constriction entrance to the SSSV, with little or no erosion observed through the SSSV itself. As the extraction rate is increased from 200 to 400 MMSCF/d a 9 fold increase in the erosion rate density is observed.

1. Introduction

Natural gas usage continues to grow as cleaner energy demands increase, with Western Australia holding over 60% of Australia's gas reserves. Chevron is one of the largest holders of natural gas resources in Australia and is planning to commercialise its Carnarvon Basin natural gas resources through the Chevron operated Gorgon Project and its 100 percent interest in the Wheatstone Project. Big Bore completions utilise 9-5/8 inch production tubulars, potentially offering economic benefits over conventional wells by allowing increased gas extraction rates. However, few Big Bore wells operate in the world, offering limited information on operating at high extraction rates for the entire well life. For safe operation the maximum gas extraction rate is required to be specified for the Big Bore wells.

Extracted raw natural gas flows as a mixture of hydrocarbon gases, condensate and sand, causing erosion damage through solid particle impact or liquid droplet impingement. Erosion prediction allows well service life to be estimated and identification of critical erosion locations like the subsurface safety valve (SSSV). Erosion damage to the metal to metal seals and the flow tube around the SSSV can result in loss of well control causing potential environmental, safety and business risks. SSSV failure is both expensive and complex due to it being located hundreds of meters below mud level to prevent hydrate formation during long term shut-ins or cold start-up (Perrin 1995).

The American Petroleum Institute's Recommended Practice 14E (API RP14E) is an industry guideline for the treatment of erosive services and suggests limiting flow velocity. The velocity defined by API RP14E (American Petroleum Institute 1991) is given by:

$$V_e = \frac{C}{\sqrt{\rho}} \tag{1}$$

where V_e is fluid erosional velocity limit in ft/s, ρ is the fluid density in lbs/ft^3 and C is a constant. API RP14E states that for corrosion and solid free services C values of 100 are conservative and C values of 150 to 200 for continuous service or 250 for intermittent service may be employed, however it offers no guide for sand laden fluids (American Petroleum Institute 1991) . Figure 1 demonstrates the relationship between the gas velocity and the API C value for a typically found gas–condensate reservoir of the North West Shelf (NWS) of Western Australia. The figure is based on a composition from table 1, a reservoir pressure and temperature of 4500 psi and 110°C respectively, and a velocity just below the wellhead for the 7" and 9-5/8" tubing and the maximum velocity within the SSSV. Fields within the NWS have reported continuous C factors as high as 380 and an intermediate C factor up to 630 with no significant metal loss (Hicking et al. 1998). Equation 1 fails to account for other important factors that influence erosion besides fluid density.

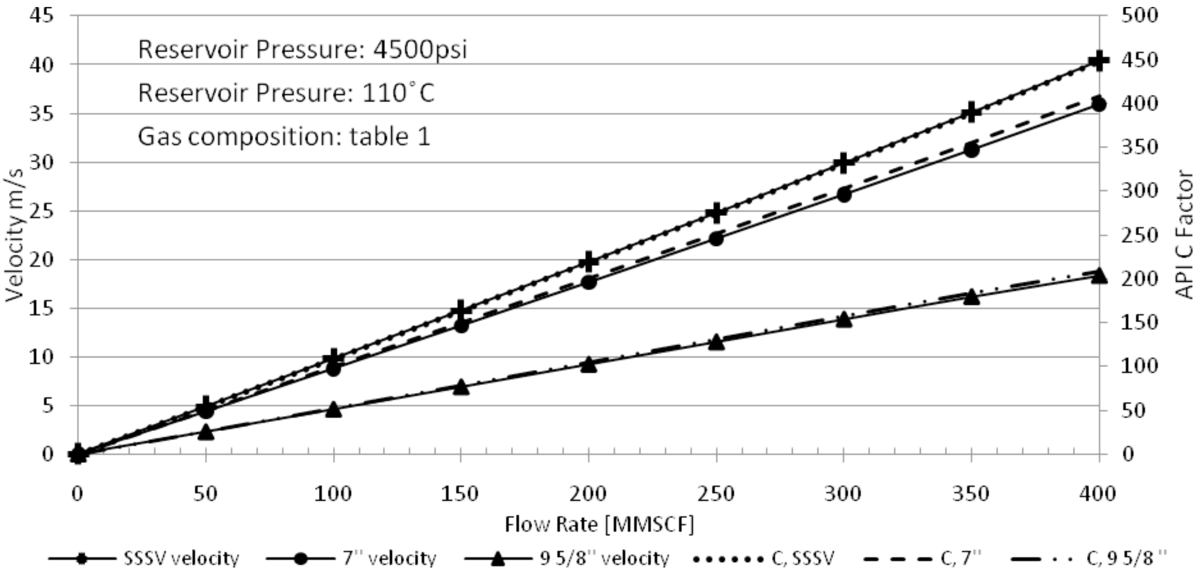

Figure 1: Comparison of flow velocity, extraction rate and API RP14E C factor for various completion arrangements.

In recognition of the limitations of API RP14E, in the presence of sand, models have been developed to predict erosion. The Sand Production Pipe Saver (SPPS) program, developed by the University of Tusla, estimates penetration rates of various piping material in sand rich environments (McLaury & Shirazi 1998). The erosion ratio and penetration rate are defined by the follow equations:

$$ER = AV^n f(\theta) \tag{2}$$

$$f(\theta) = b\theta^2 + c\theta \qquad \text{for } \theta \le \alpha \tag{3}$$

$$f(\theta) = x\cos^2(\theta)\sin(w\theta) + y\sin^2(\theta) \qquad \text{for } \theta > \alpha \tag{4}$$

where *ER* is erosion ratio [kg/kg], n is a empirical constant, equal to 1.73 for a large variety of materials, A is a material based constant, and f(θ) a function of impingement angle, with α, b, c, w, x, y and z are material specific empirical constants. The penetration rate is given by:

$$P = \frac{\dot{S}}{\rho_m N_p w_d L} ER \qquad (5)$$

where $\dot{S}$ is sand rate, N_p is the number of particles, ρ_m is the target material density and $w_d L$ is the particle impingement area. The SPPS program models the fluid as pure methane, ignoring possible influence on erosion by the increase in density due to heavier hydrocarbons present in actual gas flow. The numerical and experimental work for constrictions is predominantly based on flow through geometries significantly smaller than the diameter of a Big Bore well (McLaury et al. 1996).

This project will analyse the effect of increasing the extraction rate between 200 and 400 MMSCF/d on a generic 7″ (177.8mm) tubing retrievable subsurface safety valve (TRSSSV) with fluid and conditions typically found in the gas-condensate reservoirs of the NWS. Given the limited work conducted on erosion through a TRSSSV in the gas industry the project will provide an improved understanding of the flow characteristics and erosion through a TRSSSV. The research will demonstrate how changes to the Big Bore design, within the vicinity of the TRSSSV, influence erosion rate and aid in the development of practices that will maximise productivity, whilst still maintaining well reliability and safety.

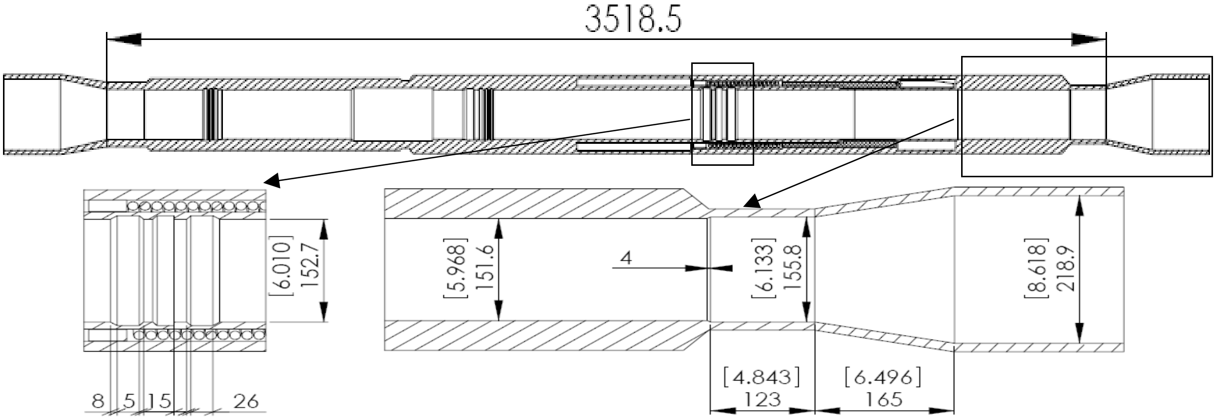

Figure 2: TRSSSV geometry and connection to 9-5/8" flow tubing (dimensions: square brackets are inches, no-brackets are mm)

2. Modelling Process

The analysis of the flow and erosion within the vicinity of the TRSSSV is conducted in the computational fluid dynamics program, Ansys CFX. Ansys CFX uses the finite volume technique to solve the Navier-Stokes equations in their conservation form. This method divides the geometry into small computational regions called control volumes. As the Navier-Stokes equations have no known general analytical solution the equations are discretised and solved iteratively for each control volume.

The turbulent flow through the TRSSSV is resolved using the k-ε model. The quantity k is the turbulence kinetic energy and ε the average turbulence dissipation rate. A limitation of the k-ε model is its inability to resolve the flow in regions where the viscous effects dominate the turbulent effects, like near wall regions (Launder & Spalding 1974). This is overcome using a scalable wall function. This places the first node at the edge of the viscous sublayer, ensuring the turbulence equations are not solved at the wall itself but flow near the wall is approximated by a logarithmic wall profile (Grotjans & Menter 1998).

The grid needs to adequately resolve the geometry, with the grid density refined in areas where the desired parameter's gradient is high, for example near walls or geometry changes. Inflation layers are inserted near the walls, using prismic elements, to ensure that at least 10 nodes lie within the boundary layer. The volume mesh consists of tetrahedral elements that have been refined by reducing face lengths and angles of resolution until the flow domain solution and erosion is independent of the mesh size. The regions upstream and downstream of the TRSSSV are extended in length to allow the formation of a fully developed turbulent profile and to examine the effects of particle impacts within these regions.

The number of particles modelled is chosen to be representative of the actual particle number. To account for the difference the particle number is scaled by the true particle mass flow rate. Particle numbers are varied from 1000 to 200,000 for mesh sizes ranging from 6000 to 2.8 million elements. The maximum erosion rate density becomes independent of grid size and particle number, at 1.3 million elements.

The TRSSSV inlet and outlet boundary conditions are based on a 3400m length, 9-5/8″ 47 lb/ft (244.5mm) production tubing. The reservoir pressure is taken as 4500 psi (31MPa) at 230 F (110°C) (WAPIMS 2007). Based on an energy balance of the wellbore the temperature at the TRSSSV inlet is set to 102°C. The static pressure is defined at the inlet based on the pressure drop from the reservoir due to frictional losses, fluid acceleration and the gravitational force. The mass flow rate is specified at the outlet and the walls have a roughness of 15 microns with no-slip condition. A modified Redlich-Kwong equation of state is adopted to determine constituent properties of the assumed compressible gas composition given below:

	Molar %	Mass %
N_2	1.9	1.20
CO_2	3	5.8
CH_4	78.4	55.7
C_2H_6	6.6	8.8
C_3H_8	3.6	7
C_4H_{10}	2.05	5.3
C_5H_{12}	1.05	3.4
C_6H_{14}	3.4	12.8

Table 1: Modelled gas mass and molar composition

The particles are assumed to have a flow rate of 0.22 lb/MMSCF, a density of 2650 kg/m^3 and a mono-dispersed, 45 micron diameter. Particles are uniformly injected at the inlet from random positions. The particles effect on the carrier fluid is assumed negligible given their small volume fraction. Lagrangian particle tracking is used to predict the particle position and velocity within the fluid domain. The particle position and velocity are given by:

$$x_i^n = x_i^o + v_{pi}^o \delta t \tag{6}$$

$$m_p \frac{dv_p}{dt} = F_D + F_B + F_R + F_{VM} + F_P \tag{7}$$

where *o* and *n* refer to old and new values respectively, v_{pi}^o is the initial particle velocity at timestep δt, m_p is particle mass, v_p is the new particle velocity, F_D is the drag force acting on the particle, F_B is the buoyancy force due to gravity, F_R is the centripetal and coriolis forces, F_{VM} is the virtual mass force and F_P is the pressure gradient force. The fluid velocity is decomposed into mean and fluctuating components. The dispersion of particles is due to the fluctuating component of the fluid velocity. The turbulent fluctuations are modelled by a normally distributed random number about a mean value.

Erosion is based on the Finnie model given by:

$$ER = AV^{n}f(\theta) \tag{8}$$

$$f(\theta) = \frac{1}{3}\cos^{2}\theta \qquad \text{for } \tan(\theta) > \frac{1}{3} \tag{9}$$

$$f(\theta) = \sin(2\theta) - 3\sin^{2}(\theta) \qquad \text{for } \tan(\theta) \le \frac{1}{3} \tag{10}$$

where ER is the Erosion Ratio in kg particle impact/kg of material removed, V is the impingement velocity in m/s, A is an erosion parameter constant, n is the coefficient of velocity set to 2 and f(θ) is the impingement angle function.

3. Results and Discussion

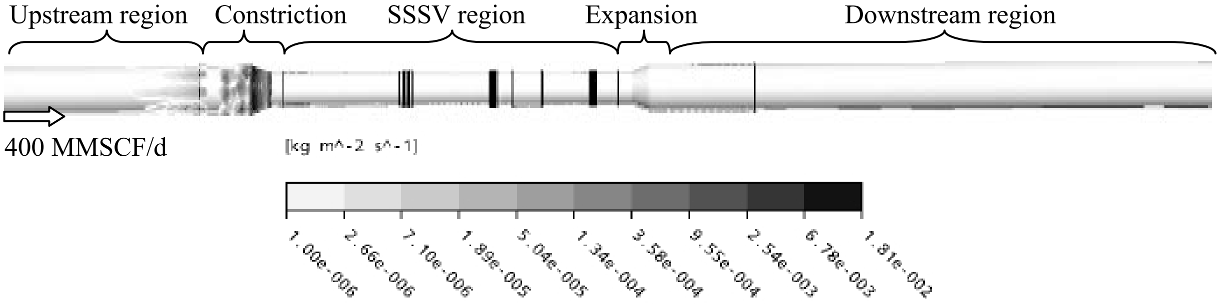

Figure 3: Erosion pattern observed within the TRSSSV region

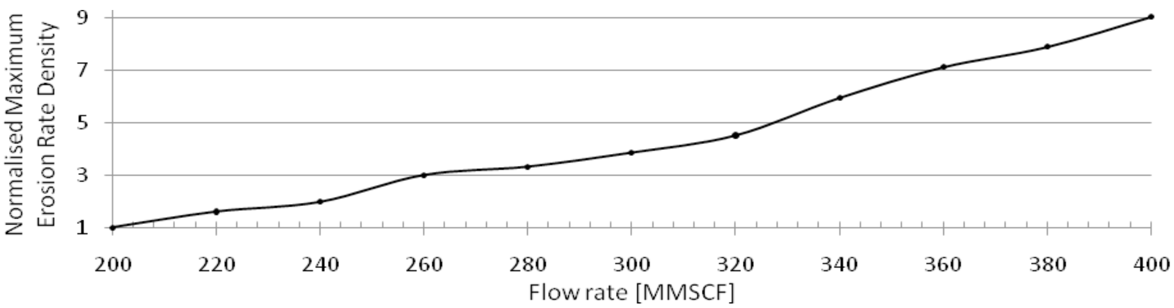

Figure 4: Normalised Maximum erosion rate density within the TRSSSV region

The erosion locations in Figure 3 remain unchanged as the flow rate increases from 200 to 400 MMSCF/d. The maximum erosion occurs within the constriction however, erosion is also prominent within the upstream region. From Figure 4, which demonstrates the normalised maximum erosion rate density, a linear increase in erosion is observed, with a 9 fold increase in erosion rate density occurring when the flow rate is 400 MMSCF/d. The higher flow stream velocity provides the sand with greater momentum, thus increasing erosion rates.

The erosion is largest in the constriction due to direct impingement. The particles' momentum is sufficient to cross the fluid streamlines as the momentum exchange between the particles and gas is small. Within the SSSV region there is no mean velocity in the radial direction. For impingements to occur the flow must provide sufficient radial momentum to the particles for them to cross the flow streamlines and impact the wall. The turbulent kinetic energy affects the size of the turbulent fluctuations in the flow. The largest values of turbulent kinetic energy are concentrated near walls and between grooves, within the SSSV. The turbulent kinetic energies however are small, with few (if any) particle impacts being observed. Recirculation is observed to occur within the SSSV grooves and the expansion. However the velocities in these regions are very small and the presence of any particle in these regions results in negligible erosion.

4. Conclusions and Future Work

CFD-based erosion prediction is presented in this paper. Modelling of a 7" TRSSSV, within a 9 5/8" production tubing arrangement is performed. The model identified the constriction between the 9 5/8" tubing and TRSSSV as the critical erosion location. An increase in flow rate from 200 through to 400MMSCF/d was observed to increase the erosion rate density up to 9 times.

Continuing work on the effect of particle size and particle rate on the erosion in the region is being conducted. A comparison of different erosion models is to be conducted due to the limited availability of erosion data in the TRSSSV. This will provide a broader range of expected erosion rates. Future work will need to investigate the influence of liquid within the flow, particularly the presence of a liquid squeeze film and liquid particle impingements.

5. Acknowledgements

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