PORE PRESSURE EVOLUTION AND CORE DAMAGE: A COMPUTATIONAL FLUID DYNAMICS APPROACH

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ABSTRACT

During tripping out of the hole, core is submitted to a relatively sudden decrease in pressure which leads to fluid expansion and movement out of the pore space into the borehole. It is widely recognized that the rapidly expanding fluids can generate fractures where the tensile stress created exceeds the tensile strength of the rock. Ideally, tripping rates should be established for each particular core during the planning phase, but common practice tends to be based on generic rules of thumb. The resulting schedules can lead to unjustifiably long tripping out operations just “to be in the safe side”, or core damage if the process is too fast. There is a lack of clarity and consensus regarding tripping schedules which impacts on both the integrity of the core and the economics of coring. With high daily rig costs, a more scientific and quantitative approach, tailored to particular core and reservoir-fluid characteristics, is required. This is particularly important for coring shale gas reservoirs. In this paper we describe the application of Computational Fluid Dynamics (CFD) to model transient pressure differentials in a gas reservoir core during retrieval. The model was constructed to represent a 3D cylindrical core. Flow of fluid within the porous media and its restrictions were calculated and compared for different pressure and time scenarios. Rock failure criterion has been based on the principle that the maximum tensile stress in the core is at maximum equal to the rock’s tensile strength. The results support and confirm empirical evidence that the pressure differentials created in a core during core retrieval are very low for relatively high permeability rock (300 mD). As the core permeability decreases the time required for the core internal pressure to approach the external pressure increases, requiring longer equilibration times. The model realisations demonstrate that a tensile failure criterion is more likely to be reached during the final last stages of the trip. The extreme case of a very low permeability rock (shale) of 0.00001 mD shows high differential pressures throughout the maximum simulated trip time of 12 hours, suggesting that pore pressure release damage is expected in shales during normal, economic tripping operations. The methodology can be adapted and extended to include the effects of mud cake, as well as multiphase flow modelling (relative permeability) for core recovery in oil reservoirs.

INTRODUCTION

It is widely recognized in the oil industry that core damage during coring is a major concern when measuring properties from cores [1, 2, 3, and 4]. Non-representative or damaged core will compromise the quality of the results obtained in any core analysis programme, producing misleading results. Core damage associated with coring operations may occur by different mechanisms: external stress release during drill-out; pore pressure release during retrieval; temperature reduction; and exposure to non-native fluids. Only the second mechanism - pore pressure release when tripping out the core - has been considered in the present study. Common practice is to make a rough estimate of the tripping rates to avoid fluid expansion damage, based on the coring contractors' experience. The resulting schedules tend to be rules of thumb and can be too short, inducing core damage, or unjustifiably long, affecting the project economics. They are normally not specifically designed for a particular core or formation. With high daily rig costs a more scientific and quantitative approach is required to justify the planned tripping schedules, especially in coring shale gas formations where damage may be more subtle and more influential than in higher permeability formations. Historically, modelling of pore pressure release on core retrieval has been based on analytical solutions. For example, Hettema *et al* [2] and Holt [3] used poro-elastic theory to estimate tensile failure as a result of pore pressure release on core recovery based on the calculation of a pore pressure diffusion time derived from core geometry and fluid and rock petrophysical and elastic properties. Our approach is to use a numerical transient model and develop a workflow which is ultimately capable of predicting optimal core tripping out time/rates to minimize the potential for rock failure by pore pressure release.

In this study, CFD is used as the tool to estimate the pressure drop across a core during retrieval. Amongst other applications, CFD enables the study of the dynamics of flow in porous media. A computational model is initially constructed to represent any specific system or device – such as a core of permeable material – and the flow of fluid within the porous media and its restrictions are calculated and compared for different pressure scenarios. The fluid flow physics are applied to this virtual prototype, and the software will output a prediction of the fluid dynamics and related physical phenomena. Very complex, non-linear mathematical expressions that define the fundamental equations of fluid flow and materials transport are incorporated. These equations are solved iteratively using complex computer algorithms embedded within CFD software. The methodology has been successfully applied in near-well bore inflow prediction models [5 and 6].

PRINCIPLES

The technology enables the prediction of fluid flow, heat and mass transfer, among other phenomena, through the discretisation of the domain of interest and numerically solving the constitutive equations on each of the discrete elements, honouring a set of boundary conditions and imposed closure terms. The equations solved are the continuity equation (mass conservation) (1) and the general momentum conservation equation. Porous media are modeled by the addition of a momentum source (2) term to the general momentum equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v_j) = S_m \qquad (1)$$

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\, \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho |v| v_j \right) \qquad (2)$$

where:

ρ: fluid density
v: velocity
S_m: source term for the continuity equation
t: time
S_i: source term for momentum equation
D: viscous resistance (permeability)
μ: fluid viscosity
C: inertial resistance factor matrix (non-Darcy effects)

For this study, the rock failure criterion has been based on the principle that tensile failure will occur when the maximum effective tensile stress developed on core depressurisation exceeds the rock's tensile strength:

$$\Delta P_{core} \geq \sigma_t \qquad (3)$$

The effective tensile stress is defined as the difference, ΔP_{core}, between the pressure in the pore system at the centre of the core (internal pressure) and the hydrostatic pressure (mud weight) at the outside edge of the core (external pressure). Rock tensile strength is based on Murrell's failure criterion [7] which predicts that the tensile strength is around $1/12^{th}$ of the rock unconfined compressive strength.

WORKFLOW

The general steps followed for the numerical simulation phase were:

- The core geometry was initially created based upon a cylindrical 3D, 4 inch diameter core;
- Once the geometry was established, a mesh was generated, as shown in Figure 1;
- Boundary conditions were assigned;
- A porous media single phase compressible gas (methane) model was selected;
- Fluid and rock material properties were assigned: density, viscosity, inertial resistance coefficient (non-Darcy flow) and permeability;
- Total core retrieval time was assigned;
- Solutions were computed and monitored;
- Results were analysed and data extracted (see example of pressure contour in Figure 2).

In the present analysis, a generic illustrative failure criterion of 100 psi tensile strength (corresponding to 1200 psi compressive strength) was applied to determine rock failure under the simulated conditions, and assumed no mud cake. However, the analysis can be easily applied to rocks of different strengths, and the CFD model can incorporate a low permeability mud cake extending from the outside of the core.

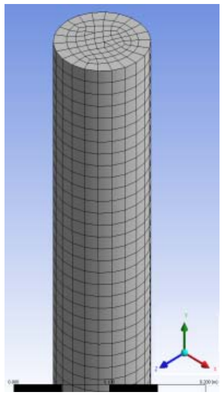


Figure 1 Representation of a fluid region of porous media flow discretized into a finite set of control volumes (mesh)

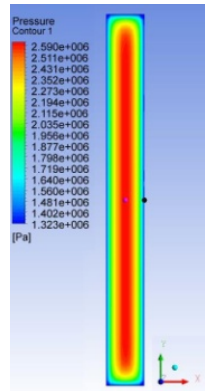
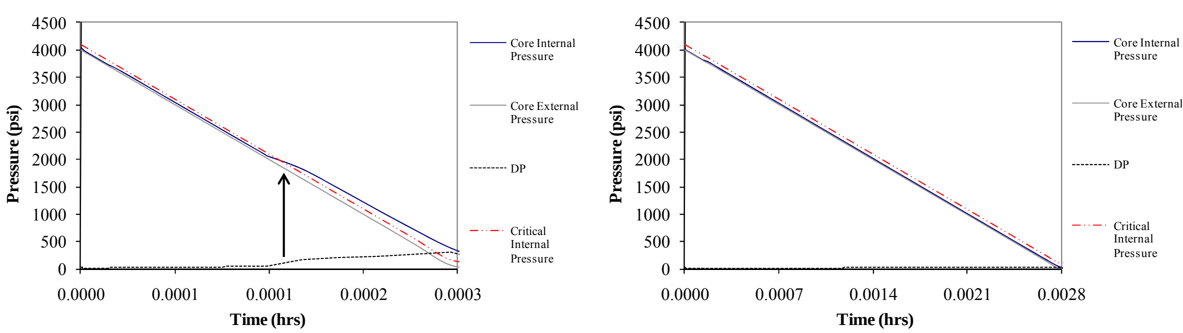


Figure 2. Example of a pressure contour for a longitudinal "slice" of core

SIMULATION RESULTS AND DISCUSSION

Several cases were run to determine potential of rock failure during core tripping out on porous media of 3 different permeability ranges at various total tripping times. Some of these are wholly implausible - for example tripping to surface from around 9,000 ft depth in seconds rather than hours - but they are used here to define the limits of the analysis and to demonstrate the process. Figure 3 shows the 1 and 10 second simulation results of core internal and external pressures and pressure differentials, as a function of time for a 300 mD core as it is brought from the reservoir (at 4000 psi pore pressure) to atmospheric pressure (rig surface). For the 1 second simulation, the difference between the core internal and external pressures remains below the maximum acceptable effective tensile stress limit (100 psi tensile strength) until 0.00013 hrs (0.47 sec) is reached, at which point the core internal pressure ΔP_{core}, exceeds the critical tensile strength. The 10 second simulation shows that ΔP_{core} is less than 38 psi throughout the retrieval process.



1 sec core tripping time 10 sec core tripping time

Figure 3: Internal-external pressures and DP versus time for a core of 300 mD

The results of pressure evolution obtained for a 0.001 mD rock for 1 second, 10 minutes, 6 hrs and 10 hours cases are shown in Figure 4. For a very short retrieval time (1 second) the core internal pressure remains constant as the depressurisation takes place, with high pressure drops developing within a few milliseconds. As the tripping time is allowed to increase (10 minute case), the core internal pressure starts to decline significantly compared to the 1 second case. A more realistic run with a total time of 6 hours shows the pressure differential within the core exceeds 100 psi for the final 1.77 hours. For a total tripping time of 9.5 hours, the core differential pressure exceeds 100 psi at 8.37 hours. These results confirm the rule of thumb that slower tripping speeds should be used in the final retrieval stages to avoid core damage when approaching the rig floor.

Results obtained for the case of a very low permeability rock of 0.00001 mD, simulating a shale, are presented in Figure 5.

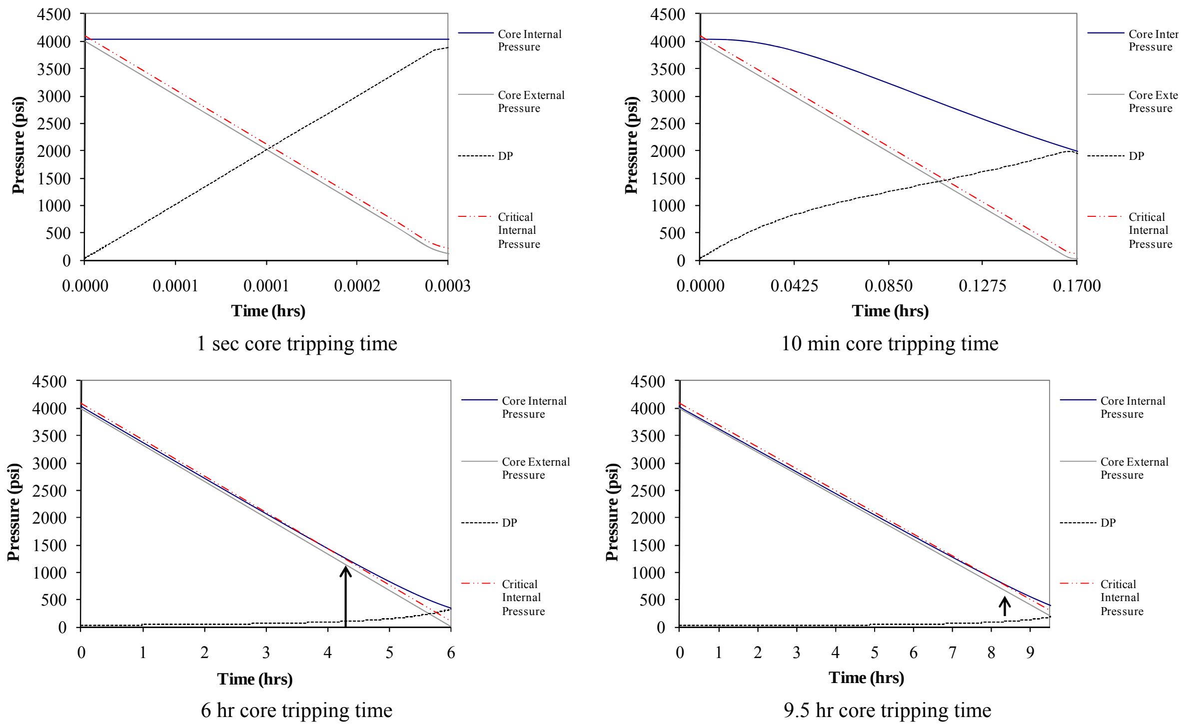


Figure 4. Internal-external pressures and DP versus time for a core of 0.001 mD

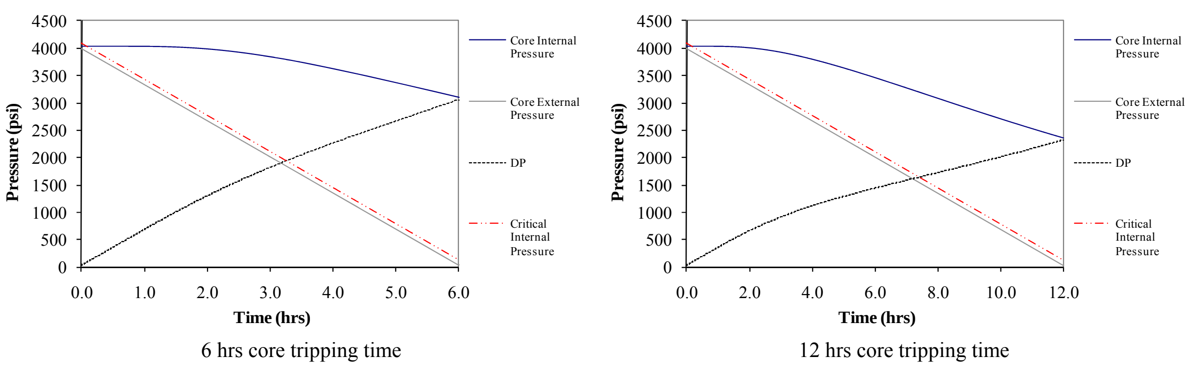


Figure 5. Internal-external pressures and DP versus time for a core of 0.00001 mD

For this scenario, the tensile strength criterion is maintained at 100 psi. The first case (6 hours) shows that the core internal pressure remains high during most of the trip, where a pressure differential of 100 psi is reached almost immediately at just 0.105 hrs. Further simulation with a total time of 12 hours shows a decline of the internal core pressure with time; nevertheless it proves to be insufficient as a differential pressure of 100 psi is exceeded at 0.210 hrs. The implications are that the tensile stress limit is expected to be exceeded at economic core tripping rates when retrieving low permeability shales.

CONCLUSIONS

The use of Computational Fluid Dynamics to model pressure differentials in a gas reservoir core during retrieval from the wellbore is presented. The model shows that the pressure differentials are very low for relatively high permeability rock (300 mD). As the core permeability decreases the time required for the core internal pressure to approach the external pressure increases, requiring longer equilibration times, and that tensile failure is most likely during the final stages of the tripping operation. For the extreme case of a very low permeability shale (0.00001 mD) high differential pressures are maintained throughout the whole 12 hour tripping run, and indicates that core damage in shales would be anticipated during normal coring operations. The outcomes from numerical modelling confirm the results from analytical models that pressure is almost instantaneously drained unless the core permeability is very low. In CFD simulation mud cakes can be incorporated in the analysis, and additional modelling of the effects of mud cake formation is planned. This study has demonstrated that CFD can accurately predict the pressure differentials created in a core during retrieval to surface and enables proper planning of tripping times based on the assessment of potential damage by pressure release.

REFERENCES

1. Fjær, R.M., R.M. Holt, P. Horsrud, A.M. Raaen and R. Risnes, *Petroleum Related Rock Mechanics*, Elsevier, Amsterdam : London, 2nd edition, (2008), p. 253.
2. Hettema M.H.H., T.H. Hanssen and B.L. Jones, "Minimizing Coring-Induced Damage in Consolidated Rock", (2002) SPE78156, SPE/ISRM Rock Mechanics Conference, Irving, Texas, October 20-23.
3. Holt, R.M., "Effects of Coring on Petrophysical Measurements", (1994) SCA-9407, SCA International Symposium Proceedings: SPWLA, SCA, Chapter-at-Large, p. 77 86.
4. Worthington, A.E., J. Gidman and G.H. Newman, "Reservoir Petrophysics of Poorly Consolidated Rocks. I. Well-Site Procedures and Laboratory Methods", (1987) SCA 8704.
5. Byrne, M., M. A. Jimenez, E. Rojas and E. Castillo, "Computational Fluid Dynamics for Reservoir and Well Fluid Flow Performance Modelling", (2011), SPE 144130, SPE European Formation Damage Conference, Noordwijk, The Netherlands, June 7 10.
6. Byrne, M., M. Jimenez, E. Rojas and J. C. Chavez, "Modelling Well Inflow Potential in Three Dimensions Using Computational Fluid Dynamics", (2010), SPE 128082, SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, February 10–12.
7. Murrell, S.A.F., "A Criterion for Brittle Fracture of Rocks and Concrete Under Triaxial Stress and The Effect of Pore pressure on The Criterion", Proc. 5th Rock Mech. Symp., Univ. of Minnesota", *In Rock Mechanics*, Pergamon, Oxford, Edited by C. Fairhurst, (1963), p. 563-577.