Numerical analysis of foam cement placement and reverse pumping in geothermal wells

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Keywords: Foam cement, Reverse cement placement, non-Newtonian rheology, Numerical modeling, High-temperature and high-pressure flow physics.

ABSTRACT

Foam cement has emerged as an attractive option for cementing geothermal wells due to its several key advantages. Its reduced density makes it an ideal choice in weak or fractured formations, where losses can occur. The gas bubbles in the foam cement provide excellent thermal insulation, which is crucial for minimizing heat losses when producing hot water. Also, foam cement exhibits greater flexibility compared to conventional cement, allowing it to better withstand the thermal stresses induced by temperature changes typical in geothermal wells, and hence maintain wellbore integrity.

However, foam cement low density is not always sufficient to avoid losses during its forward placement in the annular space between the tubular and the formation since, under this configuration, gravity has a negative impact on placement. This is why it is advisable to use the non-conventional reverse circulation cementing, where the cement slurry is pumped down the annulus rather than through the casing since now gravity has a positive impact on placement. This technique offers particular benefits for foam cement placement such as: lowering the risk of formation fracturing, stable foam quality, and improved displacement efficiency due to stable fluid system of lighter foam cement displacing the heavier drilling fluids.

Numerical modelling of complex flow physics for placement of foam cement presents several challenges. These include the need for modelling complex gas-liquid mixture in foam cement, non-Newtonian rheology of fluids, accounting for the compressibility and changes in fluid properties with pressure in high-temperature wells. Accurate modelling of geothermal wells also necessitates accurately representing complex well geometries, including eccentricity and irregularities. The numerical modelling in this field has evolved from simple 1D hydraulic models to more sophisticated CFD approaches. The challenge is to find an appropriate balance that captures the essential physics while remaining practical for engineering applications.

In this work, we have extended an incompressible cement placement model by incorporating both reverse circulation and compressible fluid for placement of foamed cement in high-temperature geothermal wells. The rheology is modelled using Herschel-Bulkley rheological model, with yield stress and consistency index as functions of foam quality. The compressibility of the foam cement brings in more non-linearities in the flow physics due to hyperbolic nature of the governing equations, which can result in slower convergence. Therefore, we have developed novel techniques to speed-up simulations to make the software practical for onsite engineering solutions. The newly developed models are calibrated and validated with in-house experimental data for specific foam cement formulations and operating conditions.

1. INTRODUCTION

Geothermal energy, a sustainable and reliable energy source, plays a crucial role in meeting the growing global energy demand. The integrity of geothermal wells is paramount for their long-term productivity and environmental safety. Cementing, a critical operation in well construction, provides zonal isolation and structural support. In high-temperature, high-pressure geothermal environments, conventional cementing techniques face significant challenges, including lost circulation in fractured formations and thermal stresses due to cement and casing expansion and contraction. Foam cement has emerged as an attractive alternative due to its reduced density, excellent thermal insulation properties, and increased flexibility. However, placing foam cement using conventional forward circulation can be problematic due to the unstable fluid system created by not implementing the conventional fluid hierarchy rules, and the instability of gas bubbles within the cement slurry. Gravity playing against flow, this can lead to issues like formation fracturing and poor displacement efficiency. Reverse circulation cementing, where the cement slurry is pumped down the annulus, offers several advantages for foam cement placement, including a reduced risk of fracturing, improved foam quality stability, and enhanced displacement efficiency due to a more stable fluid system. Numerical modelling is essential for understanding the complex flow physics involved in foam cement placement, especially considering the non-Newtonian rheology of the fluids, the compressible nature of foam cement, and the high-temperature, high-pressure conditions in geothermal wells. Accurately representing complex well geometries further adds to the modelling challenges. This paper presents a new module developed within the CurisIntegrity software for the numerical analysis of foamed cement placement using reverse circulation in high-temperature geothermal wells. The models incorporate non-Newtonian rheology based on the Herschel-Bulkley rheological law with foam-quality-dependent parameters, and account for the compressibility of foam cement. Novel techniques to accelerate simulations for practical engineering applications are discussed. The study investigates both quasi-one-dimensional and quasi-two-dimensional models, comparing forward and reverse pumping scenarios to highlight the benefits of reverse circulation for stable and efficient foam cement placement in geothermal wells.

2. STATE OF THE ART

A historical perspective on wellbore cementing reveals a progression in the methods and knowledge applied to ensure successful placement. The earliest efforts to understand the intricacies of cement placement in wellbores likely relied on practical experience, rules of thumb derived from field observations, and fundamental principles of fluid mechanics. The oil and gas industry has a long history of utilizing cement in wells, with established practices dating back to the early 20th century (Jones and Denis 1940). The evolution towards more sophisticated models was significantly accelerated by the advent of computer technology. This enabled the application of numerical methods capable of handling more complex scenarios and incorporating a deeper understanding of fluid dynamics. The increasing recognition of the non-Newtonian behaviour of drilling fluids and cement slurries, along with the acknowledgment of the significant impact of factors like casing eccentricity on displacement efficiency, marked a crucial transition in the field (Foroushan et al. 2021).

The state-of-the-art cement placement models vary significantly. The parallel sector, pipe and slot models do not account for azimuthal flows, thus offering only qualitative predictions (McLean et al. 1967). The one-dimensional channel lubrication models suit centralized annuli but are limited by accuracy for complex flows. The Hele-Shaw approximation model from Schlumberger is useful for slump simulations in annular gaps, while its extensions from Bittleston et al. (2002), Pelipenko and Frigaard (2004) cover more complex scenarios but are often difficult to extend to more complex behaviours. The 3D CFD models are comprehensive but can be slow for practical use. Simplified CFD models, like Halliburton’s model (Savery et al. 2007 and 2008) can be a solution to balance accuracy with reduced run time. Foroushan’s (2018) model couples the unwrapped and channel lubrication approaches and handles fluid interfaces. However, its visco-plastic flow simulation is approximate and limited to only simple well types. The Schlumberger’s 2D+1 lubrication model (Tardy and Bittleston, 2015) improves upon the Hele-Shaw model by easily simulating pipe movement and addressing annulus curvature, making it suitable for fluid displacement simulations. Furthermore, its 3D extension (Tardy 2018) removes the narrow gap assumption, by coupling the model with channel lubrication, but this model can be slow if not highly optimized. Ultimately, Schlumberger’s 2D+1 lubrication model developed by Tardy and Bittleston (2015) offers a good balance of accuracy and computational cost for practical applications. Therefore, this model has been chosen for implementation in CurisIntegrity code and improved further to incorporate compressibility introduced by foamed cements.

3. MODELS AND METHODS

3.1 Governing equations for fluid displacement

The displacement of the foam cement and other drilling fluids in the annular gap, between the casing and the well-bore, is simulated by numerically solving the equations of conservation of mass and momentum. The governing equations constitute of the transport equations for n_f number of fluids,

$$\frac{\partial(sc_i)}{\partial t}+\frac{\partial(hc_i v_\theta)}{\partial\theta}+\frac{\partial(sc_i v_z)}{\partial z}=0 \quad \text{such that: } \sum_{i=1}^{n_f} c_i = 1 \qquad [1]$$

and momentum equations in the axial and azimuthal direction,

$$\frac{1}{r_c}\frac{\partial p}{\partial\theta}-\rho g_\theta=\frac{\partial}{\partial r}\left(\mu\frac{\partial v_\theta}{\partial r}\right) \qquad [2]$$

$$\frac{\partial p}{\partial z}-\rho g_z=\frac{\partial}{\partial r}\left(\mu\frac{\partial v_z}{\partial r}\right) \qquad [3]$$

where, s and h are the section area and the annular gap, respectively. In general, the value of s and h varies with well-depth and azimuthal angle to define the well geometry and casing eccentricity. The outer radius of the casing (i.e. the inner radius of the annulus) is denoted as r_c. The independent variables are, time: t, azimuthal-direction: θ, axial-direction: z, and the radial direction: r. For each fluid i, the quantity c_i denotes the mass fraction of the fluids. The velocities in the azimuthal and axial direction are denoted by v_θ and v_z, respectively. The pressure is denoted by p, the azimuthal and axial component of gravity are denoted by g_θ and g_z, respectively. The fluid viscosity, μ, is computed by regularizing the Herschel-Bulkley equation [4] as discussed by Tardy and Bittleston (2015).

3.2 Fluid rheology

The non-Newtonian rheology is modelled for all the fluids using Herschel-Bulkley equation, where the shear stress in the fluid is calculated as,

$$\tau = \tau_y + k\dot{\gamma}^n \qquad [4]$$

The shear yield stress is denoted as τ_y; k is the consistency index, $\dot{\gamma}$ is the shear strain rate; and n is the fluid flow index. The properties of the foamed cement are influenced by the foam quality, Γ, defined as:

$$\Gamma = \frac{\text{volume of gas}}{\text{total volume}} \qquad [5]$$

Approximate empirical relations for shear yield stress and fluid flow index for foamed fluid are obtained by Chateau et al. (2008) and Ducloué et al. (2014) to be,

$$\tau_{yf}\left[\Gamma\right] = \tau_{yL} \cdot \frac{1-\Gamma}{\sqrt{1+2/3 \cdot \Gamma}} \qquad [6]$$

$$k_f\left[\Gamma\right] = k_L \cdot \left(\frac{5+3\cdot\Gamma}{5-2\cdot\Gamma}\right)^{\frac{n+1}{2}} \cdot \left(1-\Gamma\right)^{\frac{1-n}{2}} \qquad [7]$$

where, the subscript L is used for properties of the base liquid phase. The density of foamed fluid can be computed using ideal gas law for the gas phase as function of foam quality,

$$\rho\left[\Gamma\right] = \left(1-\Gamma\right) \cdot \left(\rho_L + \frac{\Gamma_1}{\left(1-\Gamma_1\right)} \cdot \frac{p_1}{R \cdot T_1}\right) \qquad [8]$$

where, the reference or the pumping state is denoted by subscript 1; and R is the gas constant of the foaming gas. The rheology of the foamed fluid is specified by the base fluid properties and foam quality.

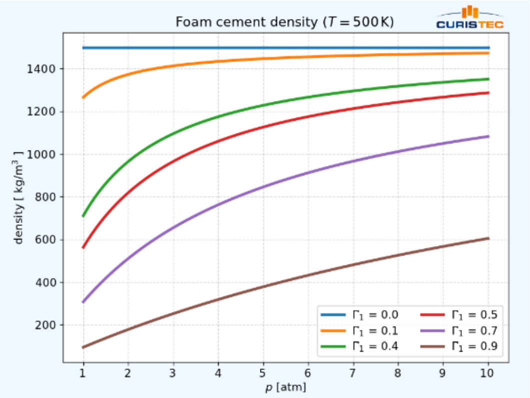

Figure 1: Variation of foam cement density vs reference foam quality.

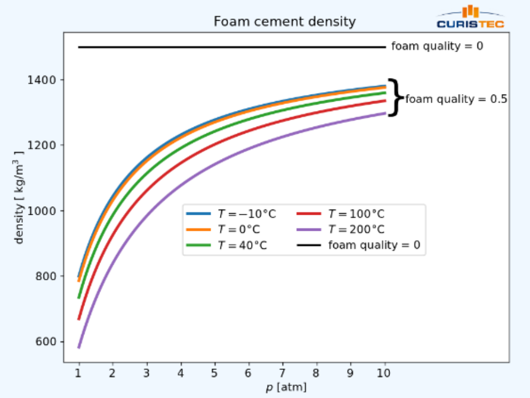

Figure 2: Variation of foam cement density vs temperature.

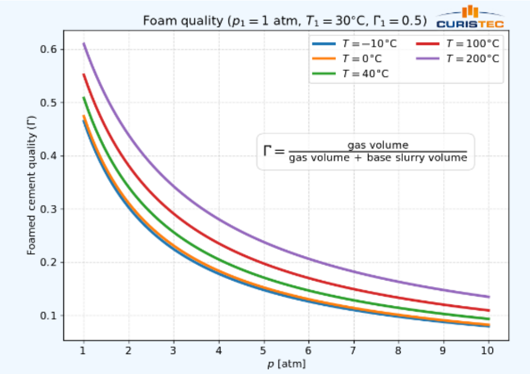

Figure 3: Variation of local foam cement quality vs temperature.

Finally, the local foam quality can be computed using the equation,

$$\Gamma\left[p,T\right] = \frac{\Gamma_1}{\left(1-\Gamma_1\right) \cdot \frac{p \cdot T_1}{T \cdot p_1} + \Gamma_1} \qquad [9]$$

Therefore, all the properties of the foam fluid can be computed using the reference or pumping conditions, local pressure and local temperature. The variation of density and foam quality as a function of pressure and temperature are shown in Fig. 1 – Fig. 3.

3.3 Numerical methods

The momentum equations [2] and [3] are reformulated as elliptic Poisson equation for pressure and solved using Cholesky decomposition. The transport equations [1] are solved using the flux-corrected transport method. This ensures sharp interfaces between the displaced fluids during the pumping operation. The equations are solved at each time-step to maintain a tight-coupling between the mass and momentum equations. A no-slip boundary condition is defined at the annular walls, a periodic boundary condition is used at the azimuthal boundary. A pressure boundary condition is specified at the outlet of the well head of annulus (for forward pumping) or at the well head of the casing (for reverse pumping). A flowrate boundary condition is specified at the well head of the casing (for forward pumping) or well head of the annulus (for reverse pumping). When pumping the foamed cement, the inlet boundary is defined using the flowrate and density of the base cement, pumping foam quality, pumping pressure and temperature. These properties are then used to compute the correct mass flow rate of the foamed cement.

4. RESULT AND DISCUSSION

The governing equations for modelling quasi-one-dimensional flow and quasi-two-dimensional flow are solved using inhouse software. The results of the simulations are presented below.

4.1 Quasi one-dimensional model

The one-dimensional model is a simplified model used to quickly access the flow instabilities and location of interfaces along the axis of the casing and annulus. It is also a useful tool for initial quick simulations (generally taking a few seconds to run) to decide an appropriate pumping sequence, pumping pressure and foam quality for effective well cementing job, before using the quasi-two-dimensional model to finalize the fluid train. Although the model is one-dimensional, it allows for changes in area, type of cross-section and radial velocity profile along the flow path. The model resolves the compressible and incompressible regions of the flow and interface locations using one-dimensional mass and momentum conservation. The 1D model from Hanachi (2018) is extended with forward and reverse pumping.

To evaluate the 1D model, we solve a similar problem as in case 2 of the two-dimensional model. The well trajectory is shown in Fig. 13. The hole diameter is 31.75 cm and casing diameter is 23.25 cm, while the thickness of the casing is neglected. The fluids are assumed to be Newtonian, with density, foam quality and consistency taken from Table. 2. The fluids are pumped in the same sequence for both the forward and reverse displacement. The foaming gas is pumped at a pressure and temperature of 52.2 MPa and 30°C, respectively. Nitrogen is used as foaming gas with a molar mass of 28.02 g/mol and gas constant of 296.71 J/kg/K. Here we look at the following two cases.

Case 1 – Forward pumping direction: The fluids flow down the casing from well-head to bottom-hole and then rise from the bottom hole into the annulus, thus cementing the annular region.

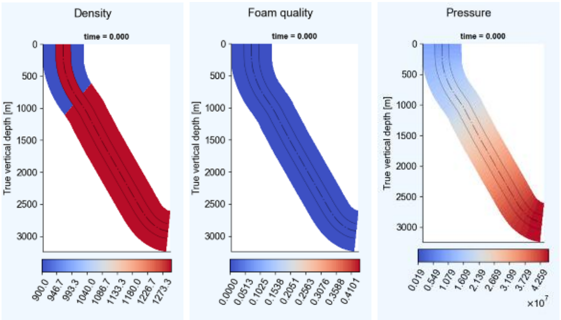

Figure 4: Initial condition of the casing and annulus before beginning the forward pumping.

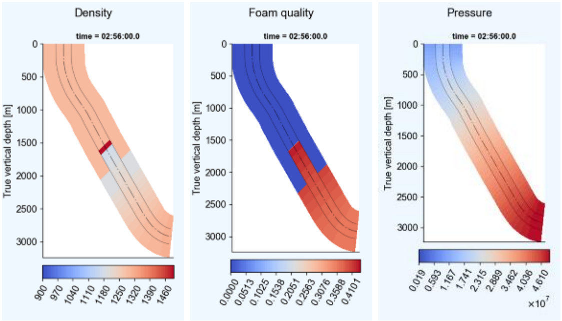

Figure 5: Foam cement placement in the well using forward pumping after 2 hours and 56 minutes.

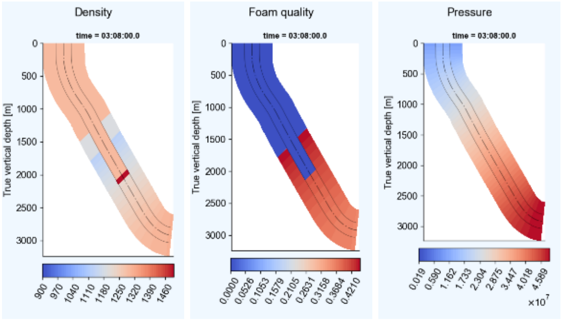

Figure 6: Foam cement placement in the well using forward pumping after 3 hours and 8 minutes.

The density, foam quality and pressure in the well at various time instances are shown in Fig. 4 – Fig. 6. In the case of forward or conventional pumping, it is difficult to control the stability and prevent mixing of the foam cement with other drilling fluids. This is because as the foam cement is pumped down the casing, the heavier fluids present in the casing maintain a stable fluid-interface until the foam cement reaches a critical depth. At this critical depth, the foam cement becomes heavier than the preceding fluid, as the high pressure at the depth compresses the nitrogen bubbles. This can result in a Rayleigh-Tayor instability, causing mixing in the casing, if this critical depth occurs before the bottom hole depth. If the preceding fluid is heavy, pre-mixing before cement-placement in the annulus can be avoided. However, after the cement enters the annulus the foam cement expands again due to reducing pressure along the flow path. This process can be observed in the density plots of Fig. 5 and Fig. 6. Therefore, the velocity in the upward direction increases rapidly to compensate for reducing density to ensure mass conservation. As the density at the interface becomes lower than that of the upper fluid, it results in a Rayleigh-Taylor instability, causing uncontrollable mixing of the fluids, thus contaminating the cement. In a one-dimensional model the mixing of fluids cannot be resolved, however, it can be used to identify and modify fluid train to minimize unstable regions.

Case 2 – Reverse pumping direction: The fluids flow down the annulus towards bottom hole and then rise from the bottom hole into the casing. The density, foam quality and pressure in the well at various time instances are shown in Fig. 7 – Fig. 9.

In the case of reverse pumping, the density of the foam cement increases as it moves down the annulus due to compression under increasing pressure. This is a self-stable configuration. The velocity decreases along the flow direction as the foam cement reaches the bottom hole, due to the increasing density. Therefore, mixing will not occur if the previous fluids present in the annulus are denser than the head-end of the foam cement at the bottom hole.

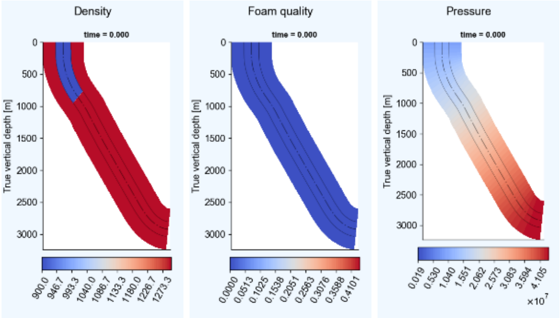

Figure 7: Initial condition of the casing and annulus before beginning the reverse pumping.

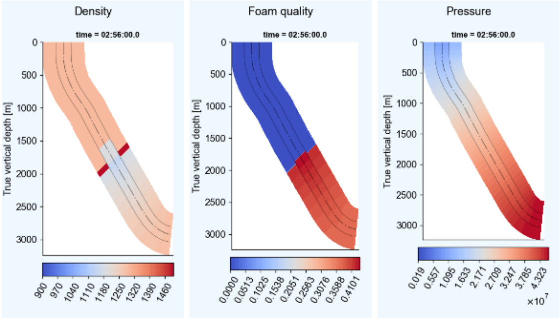

Figure 8: Foam cement placement in the well using reverse pumping after 2 hours and 56 minutes.

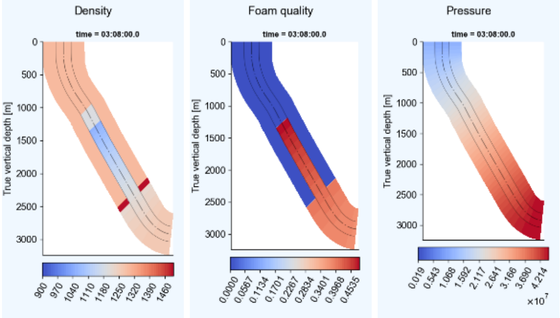

Figure 9: Foam cement placement in the well using reverse pumping after 3 hours and 8 minutes.

The fluid train, following the foam cement, can also be maintained to have lower density than the tail-end of the foam cement to ensure stability. Furthermore, the foam quality (pumping pressure of nitrogen gas) of the pumped cement can be adjusted during placement to maintain a stable configuration during the cementing job. The density of the tail and head-end of the foam cement can be obtained from the one-dimensional model. The search for an optimal fluid train and gas pumping pressures can also be automated using a 1D model to ensure a stable configuration for a given well during the cementing job.

As discussed earlier, the main advantage of the one-dimensional model compared to two- or three-dimensional model is its speed, therefore facilitating quick on-site calculations. However, it is necessary to use more sophisticated models to properly understand the mixing behaviour of the fluids, as such phenomena are not captured by the simplified 1D model.

4.2 Quasi two-dimensional model

The two-dimensional model for foam cement placement is solved in CurisIntegrity software. This is a more accurate model compared to the previously discussed one-dimensional model. In the quasi-two-dimensional model, the changes in the axial and azimuthal directions are accurately resolved using a numerical grid, while the rheology in the annular gap is modelled using analytical equations. Here we present two cases: the first simulation is with two-fluid in a vertical well, while the second simulation has five fluids sequentially pumped at different flow rates in a deviated well.

Case 1: This is a simplified scenario of cement a 1 km deep vertical well with non-eccentric centered casing. Initially there is mud filled in the casing and annulus. Foam cement is pumped from the casing at 795 litres/m for a duration of 80 minutes. The properties of the mud and cement are given in the Table 1. The hole diameter is 31.75 cm and casing inner diameter is 22.05 cm, and outer diameter is 24.45 cm. The foaming gas is pumped at the pressure and temperature of 12.4 MPa and 30°C, respectively. Nitrogen is used as foaming gas with a molar mass of 28.02 g/mol and gas constant of 296.71 J/kg/K. The fluid properties of foam are specified for the base fluid.

Table 1: Fluid properties and pumping table for case 1 of two-dimensional model.

	Fluid properties				**Pumping**	
Fluid	**ρ [g/cc]**	**τ_y [Pa]**	**k [Pa-s^n]**	**n**	**q [lt/m]**	**Γ**
mud	1.55	1	0.1	0.9	-	-
foam cement	1.8 (base)	10 (base)	0.1 (base)	0.65	795 (base)	0.3

The results of this simulation at different time instances are plotted in Fig. 10 to Fig. 12. Fluids are pumped down from the casing, hence the fluid in the annulus moves upwards. The density [kg/m^3], foam quality, and pressure [Pa] are shown in the unwrapped annular region. The foam quality is plotted as zero for non-foamed fluid (mud in this case).

As seen in Fig. 10, initially as the foamed cement rises the annulus, the fluids have a stable interface for a short duration. As the cement moves up, Fig. 11 and Fig. 12, the density of the cement at the interface decreases, and the quality of foam increases due to expanding nitrogen bubbles under decreasing pressure. This causes a Rayleigh-Taylor type instability, since the heavier mud is supported by the lighter foam cement.

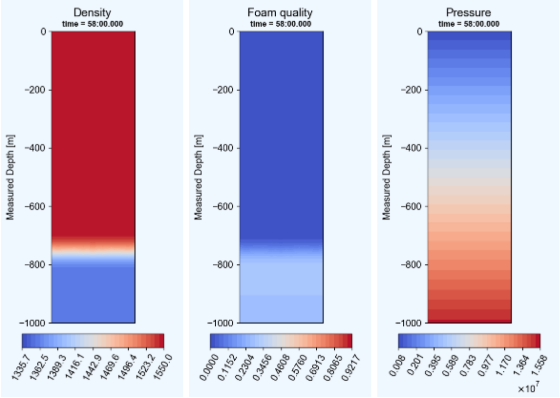

Figure 10: Foam cement placement in unwrapped annular region of vertical well after 58 minutes.

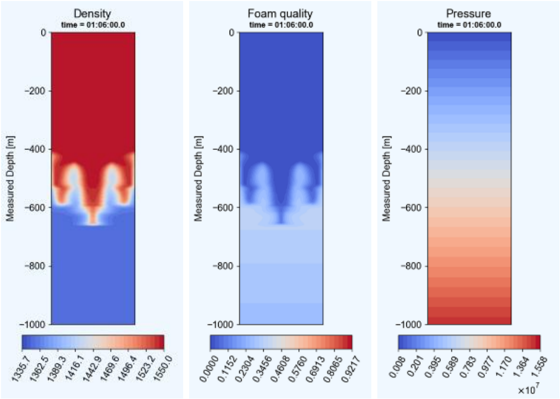

Figure 11: Foam cement placement in unwrapped annular region of vertical well after 1 hour and 6 minutes.

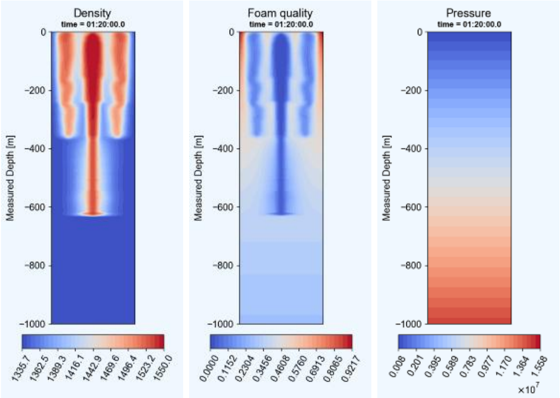

Figure 12: Foam cement placement in unwrapped annular region of vertical well after 1 hour and 20 minutes.

Case 2: In this scenario we consider cementing of a 4 km deep deviated well, with non-eccentric centered casing. The hole and casing diameters are same as in case 1. Initially there is mud filled in the casing, and the annulus has mud and spacer fluid, as seen in Fig. 14. Multiple fluids are pumped for well conditioning and cement placement in the following sequence: spacer, wash, foam cement, spacer, mud. The properties of all the fluids are given in the Table 2. The well trajectory is shown in Fig. 13. The foaming nitrogen gas is pumped at the pressure and temperature of 52.2 MPa and 30°C, respectively.

Table 2: Fluid properties and pumping table for case 2 of two-dimensional model.

	Fluid properties				Pumping		
Fluid	**ρ [g/cc]**	**τ_y [Pa]**	**k [Pa-s^n]**	**n**	**q [lt/m]**	**Γ**	**time [min]**
spacer-1	0.9	0	0.01	1	-	-	-
mud	1.3	1	0.1	0.9	-	-	-
spacer-2	1.3	0	0.01	1	1789	-	8
wash	1.2	0	0.01	1	795	-	18
foam cement	1.8 (base)	10 (base)	0.1 (base)	0.65	795 (base)	0.3	110
spacer-3	1.5	0	0.01	1	795	-	4
mud	1.3	1	0.1	0.9	2321	-	48

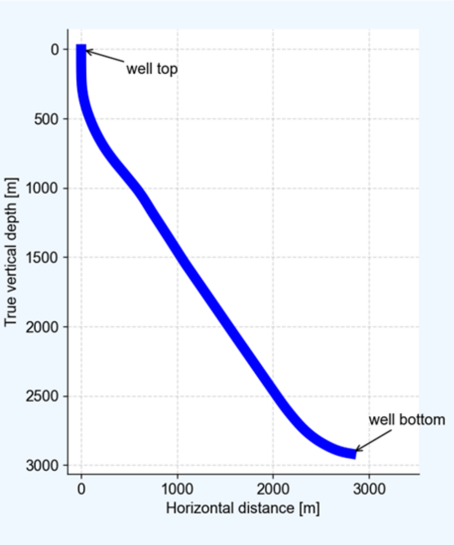

Figure 13: Trajectory of the deviated well used in case 2.

The results of this simulation at different time instances are plotted in Fig. 14 to Fig. 16. Fluids are pumped down from the casing, hence the fluid in the annulus moves upwards. The density [kg/m^3], foam quality, and pressure [Pa] are shown in the unwrapped annular region. The well in unwrapped by cutting the circumference at upper wall surface of the deviated well. The foam quality is shown as zero contours for non-foamed fluids.

In Fig. 16, we can observe the increase in foam quality as the foam cement moves up the annulus due to expansion of nitrogen bubbles with decreasing pressure. Also, in Fig. 15 and Fig. 16, we can observe that the foamed cement has slightly lower density compared to spacer-2 and wash, due to the gas phase, even though the base cement slurry is much denser than the other drilling fluids. This causes an instability at the cement-wash interface and the cement rises from the upper side of the annulus of the deviated well, as seen in Fig. 16.

The two-dimensional model has a small runtime of a few minutes making it very practical for onsite cement operations. Moreover, the model has an advantage that it resolves the mixing of fluids and provides detailed insights into the flow physics during well cementing processes.

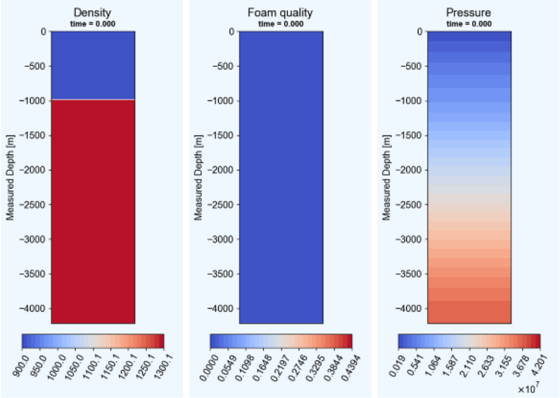

Figure 14: Initial condition of the unwrapped deviated well annulus before beginning the pumping.

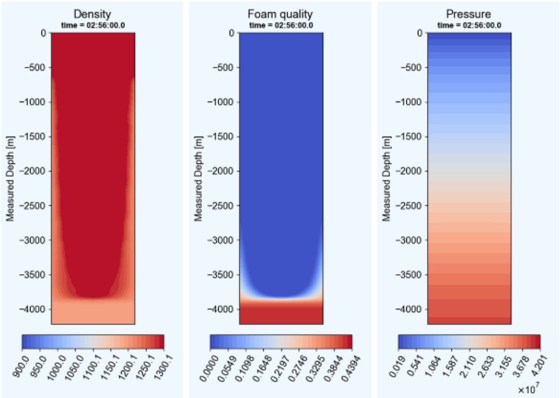

Figure 15: Foam cement placement in unwrapped annular region of deviated well after 2 hours and 56 minutes.

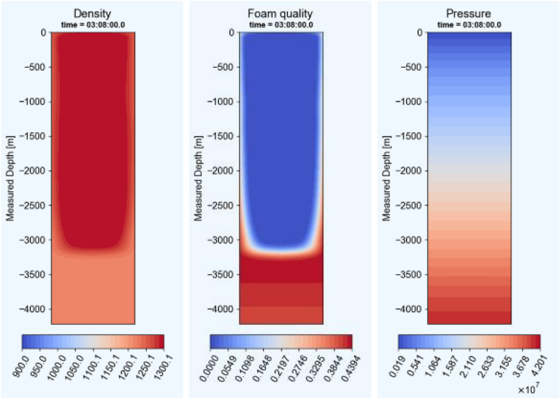

Figure 16: Foam cement placement in unwrapped annular region of deviated well after 3 hours and 8 minutes.

5. CONCLUSIONS

This study focused on the numerical analysis of foam cement placement and reverse pumping in high-temperature geothermal wells, presenting a newly developed module in the CurisIntegrity software. The complex flow physics, including the compressible nature of foam cement, were successfully incorporated into both quasi-one-dimensional and quasi-two-dimensional models. Additionally, the non-Newtonian rheology for foamed fluids was incorporated in the quasi-two-dimensional model. The investigation into forward and reverse pumping scenarios revealed the inherent stability advantages of reverse circulation for foam cement placement. The one-dimensional model proved to be a valuable tool for rapid assessment of flow instabilities and preliminary design of pumping sequences and parameters. On the other hand, the quasi-two-dimensional model provided crucial detailed insights into fluid mixing behaviour that cannot be captured by the simplified one-dimensional approach. The one-dimensional results demonstrated that reverse pumping promotes a more stable displacement front for foam cement compared to forward pumping, significantly reducing the risk of contamination and incomplete annular coverage. The developed numerical models provide a powerful tool for optimizing foam cementing operations in geothermal wells, enabling engineers to design more effective and reliable cementing jobs. The ability to accurately simulate the complex behaviour of foam cement under downhole conditions contributes to improving wellbore integrity, enhancing the long-term productivity of geothermal reservoirs, and minimizing environmental risks.

REFERENCES

Bittleston, S.H., Ferguson, J. and Frigaard, I.A.: Mud removal and cement placement during primary cementing of an oil well, laminar non-Newtonian displacements in an eccentric Hele-Shaw cell, *Journal of Engineering Mathematics*, **43**, (2002), 229-253.

Chateau, X., Ovarlez, G. and Trung, K.: Homogenization approach to the behavior of suspensions of noncolloidal particles in yield stress fluids, *Journal of Rheology*, **52 (2)**, (2008), 489-506.

Ducloué, L., Pitois, O., Goyon, J., Chateau, X., and Ovarlez, G.: Rheological behavior of suspensions of bubbles in yield stress fluids, *Journal of Non-Newtonian fluid Mechanics*, **215**, (2014), 31-39.

Foroushan, H.K., Displacement of fluids in annuli, PhD dissertation, *University of Tulsa*, Oklahoma, USA, (2018).

Foroushan, H.K., Lund, B., Ytrehus, J.D. and Saasen, A.: Cement Placement: An Overview of Fluid Displacement Techniques and Modelling, *Energies*, **14 (3)**, (2021), 573.

Hanachi, N.R., Maleki, A., and Frigaard, I.A.: A model for foamed cementing of oil & gas wells, *Journal of Engineering Mathematics*, **112**, (2018), 93-121.

Jones, P. H., and Denis Berdine.: Oil-well cementing, *Drilling and Production Practice*, American Petroleum Institute: Washington, DC, USA, (1940).

McLean, R.H., Manry, C.W. and Whitaker, W.W., Displacement mechanics in primary cementing, *Journal of Petroleum Technology*, **19 (2)**, (1967), 251-260.

Pelipenko, S.; Frigaard, I.A.: On steady state displacements in primary cementing of an oil well, *Journal of Engineering Mathematics*, **46**, (2004), 1-26.

Pelipenko, S., Frigaard, I.A.: Mud removal and cement placement during primary cementing of an oil well Part 2; steady-state displacements. *Journal of Engineering Mathematics*, **48**, (2004), 1-26.

Savery, M., Darbe, R. and Chin, W.C.: Modeling fluid interfaces during cementing using a 3D mud displacement simulator, *Offshore Technology Conference*, Houston, Texas, USA, (2007).

Savery, M., Chin, W.C. and Yerubandi, K.B: Modeling cement placement using a new 3-D flow simulator, *AADE Fluids Conference and Exhibition*, Texas, USA, (2008).

Tardy, P.M.J. and Bittleston, S.H.: A model for annular displacements of wellbore completion fluids involving casing movement, *Journal of Petroleum Science and Engineering*, **126**, (2015), 105-123.

Tardy, P.M.J: A 3D model for annular displacements of wellbore completion fluids with casing movement, *Journal of Petroleum Science and Engineering*, **162**, (2018), 114-136.

Acknowledgements

This work was carried out as part of the COMPASS project, which has received funding from the European Union’s Horizon research and innovation programme under grant agreement No. 101084623. The authors would like to thank all the partners of the COMPASS consortium for their collaboration and valuable contributions throughout the project. We would like to acknowledge the insightful contributions of Anthony Badalamenti from Curistec, whose expertise in foam cement and cement pumping operations significantly enhanced our understanding of the field applications relevant to this model. We also gratefully acknowledge CURISTEC for providing the computational resources necessary for performing the simulations presented in this work.