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# MODELING OF COMPLEX DISPLACEMENT FLOWS INVOLVING FOAMED FLUIDS IN ANNULAR GEOMETRIES FOR WELL CEMENTING APPLICATIONS

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**Abstract.** *Multiphase displacement in annular geometries is present in many industrial applications involving the substitution of fluids, such as oil and gas well cementing operation, which plays a relevant role in well integrity. For some applications, combining a low-density high compressive strength cement is required, and foamed cement is often used in these scenarios. Foamed cementing involves the generation of a cement slurry with stable suspensions of nitrogen bubbles leading to pressure and temperature dependent densities and non-Newtonian rheology. To properly model the displacement complexity involving foamed fluids, a 3-dimensional (3D) computational fluid dynamics (CFD) model was developed. The conservation and constitutive equations are solved in an annulus, taking into the effect of pressure in fluid density and rheology. The volume-of-fluid (VoF) method was used to capture the interface between fluids. A validation of the implemented models was performed using exact solutions for axisymmetric single-phase flow with incompressible and compressible fluids, and Newtonian and non-Newtonian constitutive models. Further, the multiphase simulations show the removal efficiency of the drilling fluid by the foamed cement slurry in selected scenarios. The model developed may also be suitable for other applications involving displacement flows of foamed and energized fluids.*

**Keywords:** CFD, rheology, foams, displacement, well cementing

## 1. INTRODUCTION

Well cementing is an important operation in oil and gas industry. Its objectives include zonal isolation of potential flow zones for the whole lifecycle of the well, and the support of the casing structure and protection from corrosive fluids (API, 2010). In many situations long cement columns are required to isolate multiple zones, and the operational window adequation is challenging (pore pressure and fracture gradient limits). Since the density of conventional cement slurries exceeds the drilling fluids, the cementing of long sections may become unfeasible in low fracture gradient scenarios. Non-conventional techniques - such as lightweight extended cement slurries, lightweight blends with glass or pozzolan microspheres, two-stage cementing, Managed Pressure Cementing (MPC) or foamed cementing - can solve the limitations.

Foamed cements are stable suspensions of dispersed gas (usually nitrogen) in a base cement slurry. Some of the advantages of this technique (Olowolagba, 2010, Nelson et Guillot, 2006 and Guillot, 2012) are cited:

- Low cement slurry densities with good mechanical properties and rapid compressive strength development.
- Rigorous fluid loss control without additives.
- Pressure control during cement curing (due to gas expansion), reducing the probability of annular gas flow.
- Divergence in loss-circulation zones, increasing the ability to place cement above high-permeable zones.

The stable bubble suspension - called energized fluids or foams, depending on volumetric concentration - needs a rigorous quality control. In well cementing applications, the maximum gas concentration shall not exceed 35% in volume to avoid adverse effects in compressive strength reduction, stability, and permeability to unaccepted levels (API, 2010).

For the success of the cementing operation, it is necessary that spacers and cement slurries remove the drilling fluids from the annulus. When this substitution is not fully achieved, leak paths may appear and loss of well integrity occurs. In foamed cementing applications this is not an exception. The study of the displacement of one fluid by another in annular flows, both experimentally and numerically, has been extensively performed and poses as one of the critical engineering problems (Nelson et Guillot, 2006; Foroushian, 2021). With the increase in computing power, computational fluid

dynamics (CFD) has been used for displacement simulations in well cementing applications (Enayatpour, 2017; Skadsem et al, 2019).

In foamed cement applications, the density varies with pressure and temperature due to the expansion of the dispersed gas, which allows an additional beneficial effect in the displacement by filling gaps when the expansion occurs. Other beneficial effect for the displacement is the change of rheological properties with pressure and temperature, enhancing the viscosity contrast to the drilling fluid.

Several studies focus on the rheological properties of energized fluids and foams, using theoretical, experimental and/or numerical approaches: experimental approaches measure flow behavior through flow-loops, using adapted rotational viscosimeters or stress-controlled rheometers; theoretical and numerical analysis solve bubble dispersion models (Rosenbaum, 2019, Ducloué, 2015, Olowolagba, 2010, Sinha, 2019, Sheriff, 2016, Guillot, 2012). Several alerts to avoid false readings need to be considered due to the presence of yield stress in the foamed fluids.

## 2. SCOPE OF WORK

A conceptual model is presented as scope for first step in the annular displacement with foamed fluids. The following sections describe the numerical approach for the simulation of the displacement flow using non-Newtonian compressible fluids.

### 2.1 Model Description

A Schematic of the problem is presented in Figure 1. The annular space is initially filled with the displaced fluid (*Fluid 1*) and the displacing fluid (*Fluid 2*) enters from the bottom with a constant mass flow rate ( $\dot{m}_{in}$ ). At the top of the section, a known absolute pressure ( $P_{out}$ ) is considered as boundary condition. The geometric parameters are the radius of the well ( $R_w$ ), radius of the casing ( $R_c$ ), eccentricity ( $e$ ), length of the section ( $L$ ) and well inclination ( $\beta$ ).

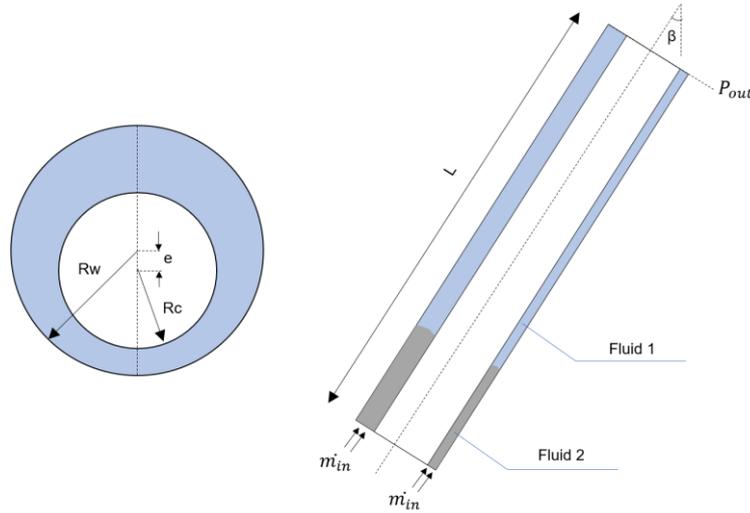


Figure 1. Schematic of the geometric and flow model of well cementing

The conservation equations of mass (Eq. 1) and momentum (Eq. 2) are applied using the Volume of Fluid (VoF) method for modeling the multiphase problem. This method solves the governing equations averaging constitutive and flow properties of the phases for each control volume, while the volumetric phase concentration is calculated through the mass conservation for each phase (Eq. 3). The sum of the volume fractions must be equal to the unity ( $\sum_1^n \alpha_i = 1$ ).

$$\frac{\partial(\rho)_{mix}}{\partial t} + \nabla \cdot (\rho \vec{U})_{mix} = 0 \quad (1)$$

$$\frac{\partial(\rho \vec{U})_{mix}}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U})_{mix} = -\vec{\nabla} p + \rho_{mix} \cdot \vec{g} + (\nabla \cdot \vec{\tau})_{mix} + F_{st} \quad (2)$$

$$\frac{\partial(\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \vec{U}_i) = 0 \quad (3)$$

The equations of state and constitutive equations used must describe fluids with pressure and shear stress dependent behaviors. In the case of the energized/foamed fluids, the density dependence with pressure follows from the definition

of the volumetric fraction, also known as Foam Quality ( $\varphi$ ), shown in Eq. 4, and the gas-liquid volumetric injection ratio at standard conditions ( $GLR_{std}$ ) in Eq. 5.

$$\varphi(p, T) = \frac{Q_{gas}}{Q_{gas} + Q_{liq}} \quad (4)$$

$$GLR_{std} = \frac{Q_{gas,STD}}{Q_{liq}} \quad (5)$$

For isothermal flow, and considering that the injected gas behaves as an ideal gas, the quality  $\varphi$  can be obtained combining Eq. 4 and Eq. 5:

$$\varphi(p) = \frac{GLR_{STD} \cdot \frac{p_{STD}}{p}}{1 + GLR_{STD} \cdot \frac{p_{STD}}{p}} \quad (6)$$

Thus, the density of the foamed fluid can be expressed by Eq. 7:

$$\rho_{foam} = (1 - \varphi) \cdot \rho_{liq} + \varphi \cdot \rho_{gas,STD} \cdot \frac{p}{p_{STD}} \quad (7)$$

Where  $\rho_{liq}$  is the density of the base liquid fluid and  $\rho_{gas,STD}$  is the gas density at standard conditions. Finally, considering  $D = (1/2) \cdot (\nabla \vec{U} + \nabla \vec{U}^T)$  as the rate of strain tensor, the constitutive equation for energized/foamed fluids is given by Eq. 8 where  $\eta(\dot{\gamma}, \varphi)$  is a viscosity function which is strain rate and gas fraction dependent (and pressure dependent by consequence). The magnitude of the strain rate is calculated with  $\dot{\gamma} = \sqrt{2} \cdot |D|$ .

$$\bar{\tau} = 2 \cdot \eta(\dot{\gamma}, \varphi) \cdot D \quad (8)$$

## 2.2 Model implementation

The 3D model was implemented in the open-source code for CFD, OpenFOAM Version 9. In the Multiphase Flow Library, the solver *compressibleInterFoam* applies for problems involving two compressible, non-isothermal immiscible fluids using VoF phase-fraction based interface capturing. However, the Equations of State and Viscosity Functions available in this solver do not reproduce the strain-rate dependence and the desired dependence on pressure of foamed fluids. Therefore, adaptations on the existing solver were performed by editing the C++ source-code to implement the desired mathematical descriptions and compiling a new adapted solver. A summary of the steps made in the source code is shown in Figure 2, based on Westermaier and Kowalczyk, 2020.

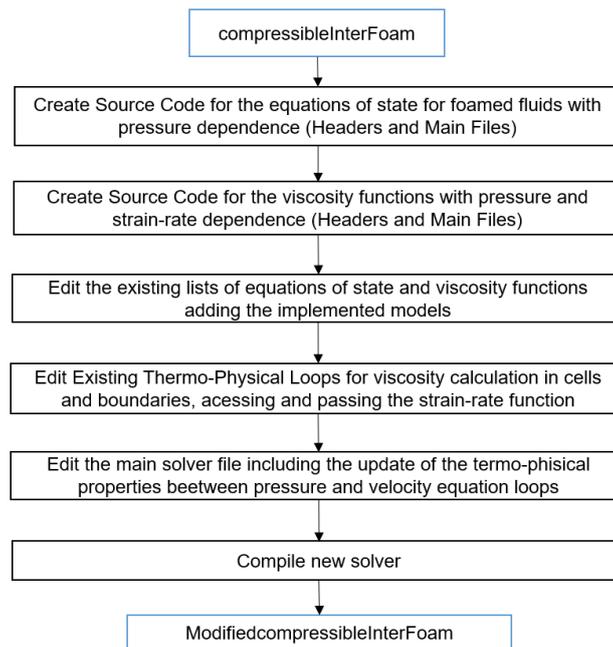


Figure 2. Steps in the implementation of the models in OpenFOAM

The geometry used in the simulations has the parameters described in Table 1, which corresponds to a typical 10 ¾ inches casing in a 14 ¾” well with 50% centralization in a vertical well. The discretization of the geometry is performed with a structured mesh 40 elements in radial direction, 800 elements in axial direction. In the case of the 3D model, 80 additional elements are considered in the angular direction. The meshes are illustrated in Figure 3.

Table 1. Geometrical parameters of the model

<b>R<sub>w</sub> (m)</b>	<b>R<sub>c</sub> (m)</b>	<b>L (m)</b>	<b>e (m)</b>	<b>β (°)</b>
0.136525	0.187325	4.0	0.0254 *	0
* For 3D simulations only				

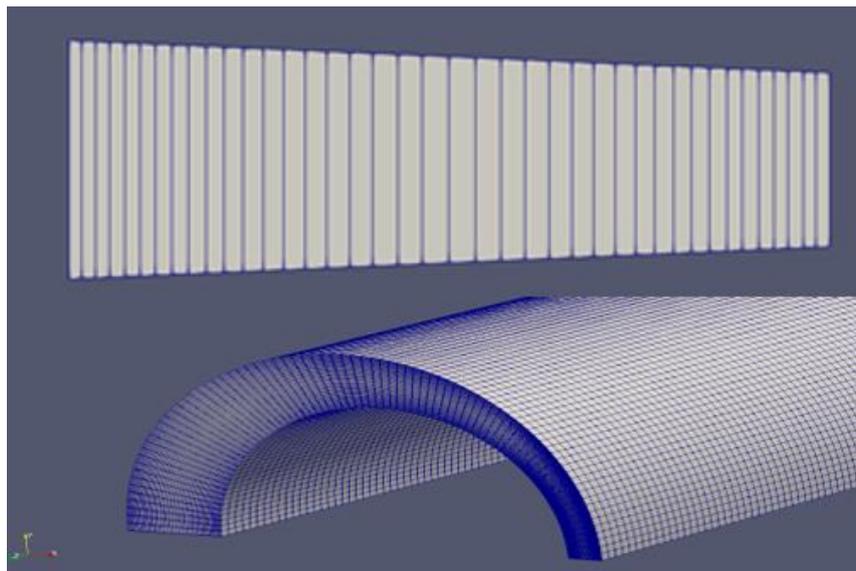


Figure 3. Discretization for the 2D and 3D model

### 2.3 Model validation

The code validation was based on solving analytically a 1-dimensional axisymmetric flow for a single-phase fluid, which has known exact solutions (Grinchik and Kim, 1974; Hanks, 1979). In this case, Eq. 2 simplifies to Eq. 9, where  $\dot{m}$  is the constant mass flow rate, A is the cross-sectional area, and  $p_{out}$  is the absolute pressure at the outlet:

$$\frac{\partial p}{\partial z} = \rho(p) \cdot g \cdot \cos(\beta) + \frac{\tau_w(p)}{\frac{H}{2}} + \left(\frac{\dot{m}}{A}\right)^2 \cdot \frac{1}{\rho^3} \cdot \frac{\partial \rho(p)}{\partial z} \quad (9)$$

The shear stress term ( $\tau_w(p)$ ) in Eq. 9 is dependent on the viscosity function for the fluid. The models tested include Newtonian, Power-Law, and Herschel Bulkley, and both incompressible and compressible cases were run in the 2D model. To validate cases of foamed fluids, the viscosity function  $\eta(\dot{\gamma}, p)$  selected account for the consistency index and yield stress dependence with gas volumetric fraction (same model used by Hanachi et al, 2018).

Table 2 and Table 3 summarize the properties of the fluids used in the validation, and Table 4 shows the flow boundary conditions.

Table 2. Fluids used in incompressible validation cases

Newtonian Fluid	Power-Law Fluid	Herschel-Bulkley Fluid
$\rho = 1000 \text{ kg/m}^3$	$\rho = 1000 \text{ kg/m}^3$	$\rho = 1000 \text{ kg/m}^3$
$\mu = 0,1 \text{ Pa.s}^n$	$k = 0,1 \text{ Pa.s}^n$	$k = 0,1 \text{ Pa.s}^n$
-	$n = 0,7$	$n = 0,7$
-	-	$\tau_y = 0,1 \text{ Pa}$

Table 3. Fluid used as compressible foamed fluid for validation cases, with Herschel-Bulkley viscosity model

$\rho_{liq}$	1000 kg/m <sup>3</sup>
$GLR_{STD}$	5 m <sup>3</sup> gas / m <sup>3</sup>
$\rho_{gas,STD}$	1,2506 kg/m <sup>3</sup> (N <sub>2</sub> in standard conditions)
$k_{base\_liq}$	0.1 Pa.s <sup>n</sup>
$n$	0.7
$\tau_{y\_base\_liq}$	0,1 Pa

Table 4. Flow boundary conditions

$\dot{m}_{in\_liquid}$	0.1723 kg/s
Outlet Pressure ( $p_{out}$ )	1 Mpa
Restrictions	Laminar Flow

The pressure and velocity profiles are presented as follows:

- Figure 4 shows velocity and pressure drop profiles for incompressible fluids in axisymmetric flow at steady state-conditions.
- Figure 5 shows absolute pressure, pressure drop and density profiles for compressible fluid in axisymmetric flow at steady-state conditions.

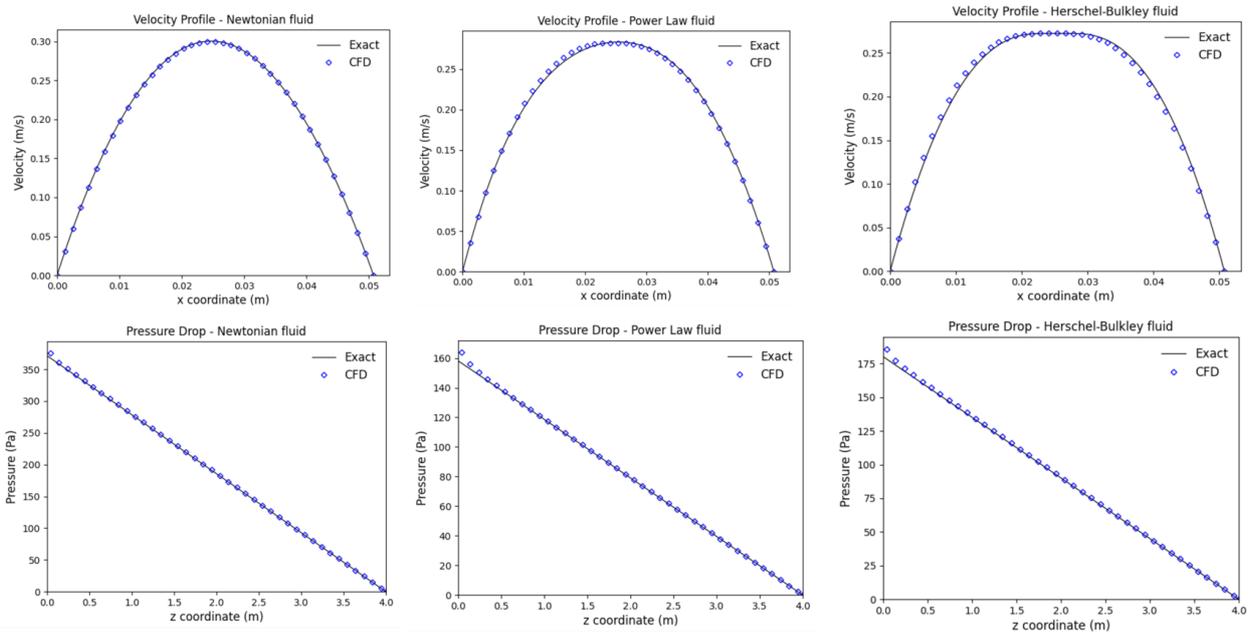


Figure 4. Validation results for velocity profile and pressure loss for single-phase incompressible simulations

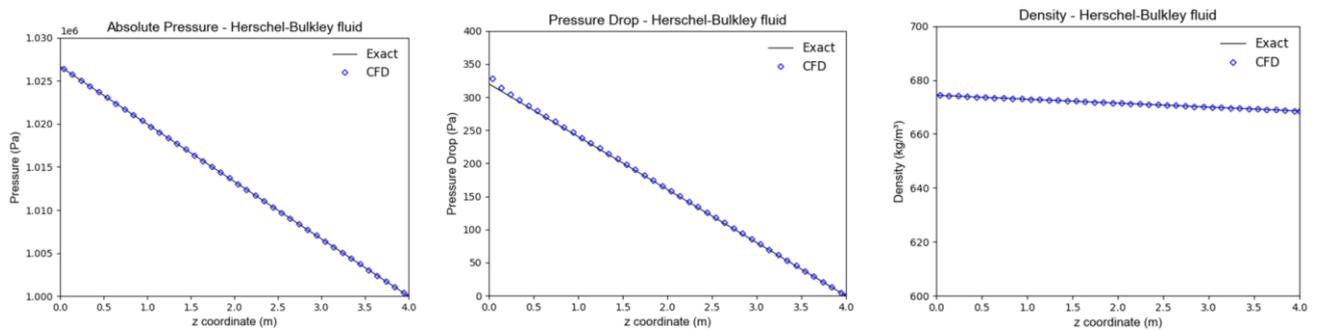


Figure 5. Validation results for pressure drop and density profile for single-phase compressible simulations

## 2.4 Results for multiphase 3D simulations

A multiphase displacement simulation in 3D geometry evaluates quantitatively the substitution of the displaced fluid by the foamed displacing fluid in an eccentric annular geometry. Table 5 shows the properties of the two fluids involved in the simulations.

Table 5. Fluid description for multiphase simulations

Property	Fluid 1 (displaced)	Fluid 2 (displacing)
Fluid Type	Constant density drilling fluid	Foamed cement
Density ( $\rho$ )	1000 kg/m <sup>3</sup>	$\rho_{liq} = 1900 \text{ kg/m}^3$ $RGL_{STD} = 4.5 \text{ m}^3/\text{m}^3$ Variable density
Consistency Index (k)	0.1 Pa.s <sup>n</sup>	$K_{base\_fluid} = 1.0 \text{ Pa}$
Behavior Index (n)	0,8	0,7
Yield Stress ( $\tau_y$ )	0.3 Pa	$\tau_{y\_base\_fluid} = 0.5 \text{ Pa}$

The results plotted are the density profile at the wide and narrow side of the eccentric annulus and the density profile in the case of fully concentric annulus; and the velocity contour in the sections filled with the foamed (displacing) fluid and in the sections filled with the displaced fluid. Both are presented in Figure 6 and Figure 7. As expected, the model

correctly predicts the preferred flow in the wide side but still shows some displacement in the narrow side, due to the expanding effect that leads to an increase of the velocity as the fluids flow upwards.

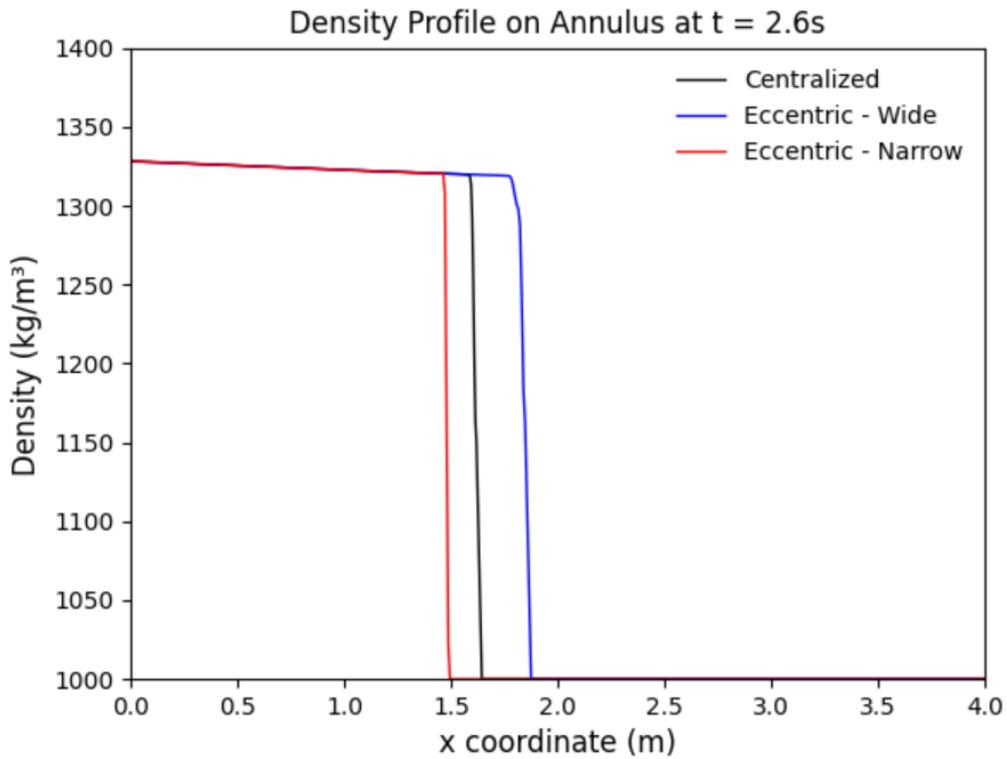


Figure 6. Average density profile at wide and narrow side of annular space at t = 2,6s.

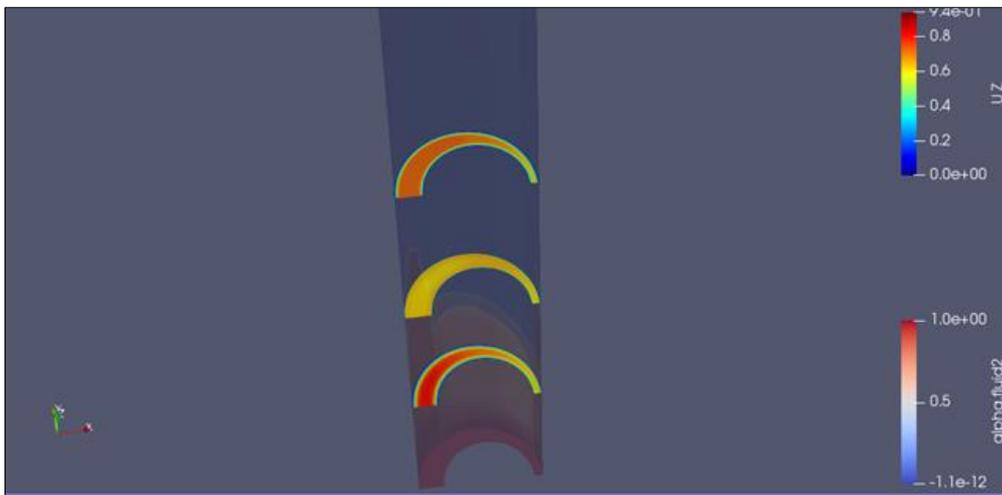


Figure 7. Velocity profile evolution with the density and rheology pressure dependence at t = 2,6s for sections at z = 0,5m; z = 1,0m and z = 2,0m.

The evolution of the displacement efficiency is another result of interest to evaluate the proper substitution of the fluids. The displacement efficiency is defined as  $Eff = \frac{V_{displacing\ fluid}}{V_{control}}$ , using the first half of the annular space as the control volume. The efficiency for fully concentric annulus and 50% eccentricity is plotted in Figure 8.

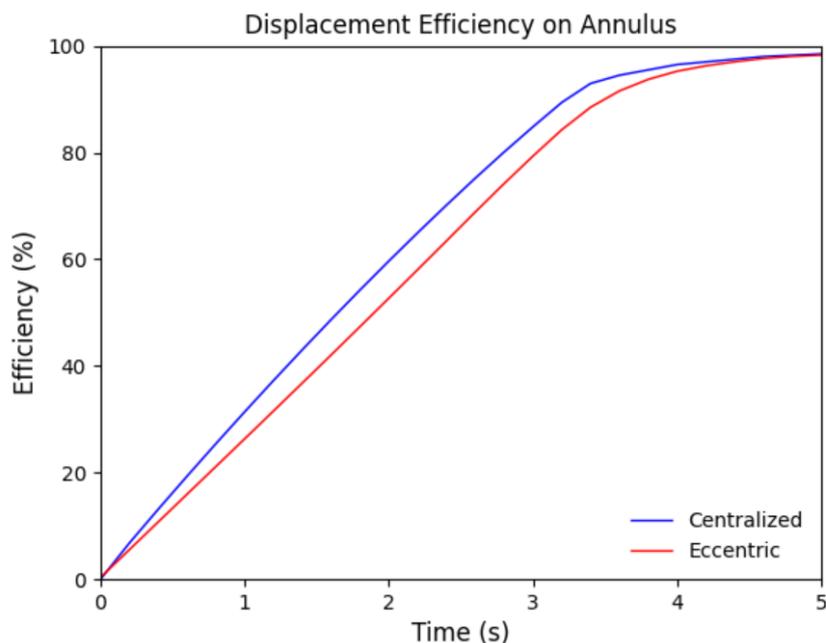


Figure 8. Displacement efficiency curves for the control volume in annular space

## 2.5 Conclusions and final remarks

A 3-dimensional CFD model was developed for energized/foamed fluid flow, with non-Newtonian behavior and pressure dependence on the density and viscosity functions. Existing CFD software require customization of equations of state and constitutive models, and a proper validation protocol was performed, using exact solutions for non-Newtonian flow combined with 1-dimensional solving of momentum equation for compressible fluids.

The multiphase simulation results correctly show the expanding effects of the foamed fluids in the displacement and the non-uniform flow in the eccentric annulus. Consequently, the model developed seems to be suitable for the analysis of different well conditions and fluid compositions, contributing to the optimization of the cementing design process. Further work include validation with experimental data, evaluation of different conditions for foamed cementing operations, and the comparison with other cementing techniques such as other lightweight cement systems.

## 3. ACKNOWLEDGEMENTS

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