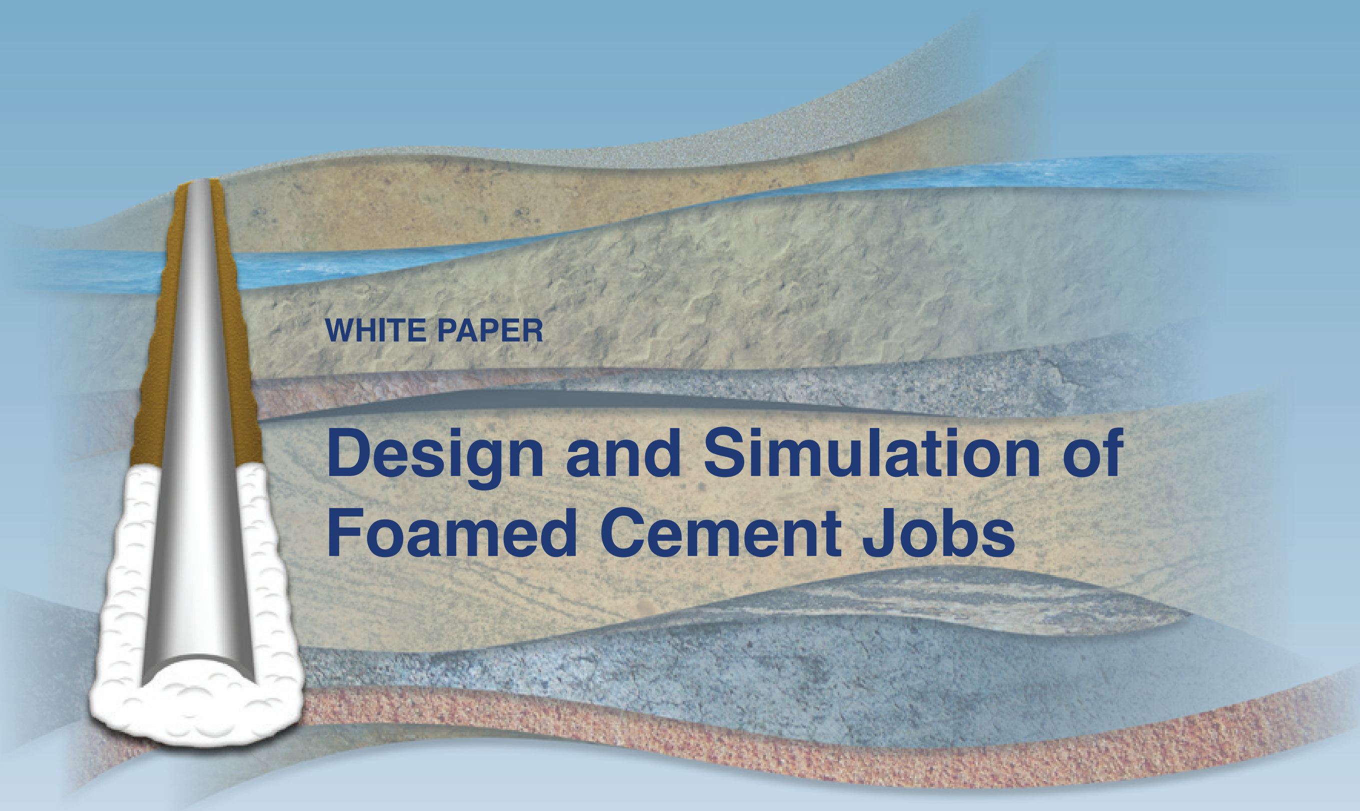
Pegasus Vertex, Inc.

Drilling Software | Sophisticated Yet Simple



WHITE PAPER

Design and Simulation of Foamed Cement Jobs

CONTENTS

I. Introduction

Many wells are drilled in areas where weak zones cannot support a cement column of normal density in excess of 15 ppg [1797 kg/m3]. These situations require the use of low density cement systems that reduce the hydrostatic pressure of the fluid column during cement placement.

Lightweight additives such as bentonite and gilsonite are used to reduce the weight of the slurry to as low as 11.5 ppg [1378 kg/m3]. The use of gas filled pozzolan spheres or hollow glass microspheres can further reduce the density of the cement to as little as 7.5 ppg [898.7 kg/m3].

Another method to reduce the density of cement is to mix cement slurries with foaming agents and gas (usually nitrogen). With foamed cements, densities as low as 8 ppg [958.6 kg/m3] can be achieved while maintaining good strength properties in the cured cement.

Foamed cement has long been regarded as an answer to the problem of effectively cementing lost circulation zones. So why has foamed cement not become the obvious choice of many producer?

The answer is that while there are many laboratory proven benefits of foamed cement, the lack of ability of the producer to grab a surface sample as a telltale indicator as to the success of the cement job leads to a situation where they must rely on the theory of foamed cement job design, the coordination of multiple fluid rates during job execution, and the ever evolving science of foamed cement job bond logging to tell them if they have a successful cement job.

While conventional cement jobs have been extensively modeled, designing a foamed cement job requires cumbersome calculations to take into account the influence of pressure and temperature on compressible fluid. In the past, design used to be based on the hydrostatic profile in the well at the end of the job, and the main parameters were the number of stages and the nitrogen ratio. However, to fully understand the hydraulic behavior of foamed slurry as functions of temperature and pressure at various times of circulations, a numerical simulator is required.

Some of the technical concerns for foamed cement operations are listed here:

- Compressibility of foamed cement slurry
- Temperature and pressure dependency
- Rheological behavior of foamed fluid
- Multi-stage nitrogen loading ratios
- Variable choke pressure
- Extended, horizontal wells
- U-tubing phenomenon with foamed slurry in wellbore
- Numerical convergence

Simulators can be used to:

- Optimize pump rates for maximum mud displacement efficiency by designing the highest allowable pump rates, without exceeding fracturing pressures.
- Predict equivalent circulating densities (ECD) at any location in the well at any specific time during the job, even during free fall when the well is on vacuum and surface pressure indication is zero.
- Quickly design and perform analyses of foamed cement jobs.
- Optimize the nitrogen loading ratios.

A function to design and simulate foamed cement job is now available in CEMPRO+, PVI's cement job simulator. It not only considers the static math model for planning purposes, but also includes the dynamic simulation of downhole flow condition. The difference of static design and actual final foamed slurry positions are studied. An optimum design with desired pressure and density profiles both during circulation and after placement can be achieved by careful planning of design parameters including density of base fluid, nitrogen ratio, number of stages and back pressure.

II. Job Design

A foamed cement job entails the injection of a known quantity of nitrogen gas into a given volume of base cement slurry and foaming agent. During the displacement, the foamed cement slurry is pumped down the casing and flows to its final annular location. Along the flow path, pressure and temperature change continuously. The higher downhole temperature tends to expand the gas phase of the fluid, while higher downhole pressure compresses it. The properties such as density, viscosity, volume and flow rate of foamed cement slurry will fluctuate, depending on the location and downhole conditions. The compressible slurry exhibits its dynamic properties different than those anticipated in lab. In general, the addition of nitrogen increases slurry viscosity, which is dependent on the foam quality (gas volume percentage).

Computer modeling of cement jobs normally addresses issues concerning pump pressure and horsepower requirement, displacement efficiency, equivalent circulating densities (ECD) at zones of interests, dynamic annular pressure profiles, etc. For foamed cement jobs, additional considerations are required including:

- Foamed cement density
- Equivalent pump-in rate
- Return rate
- Foam quality
- Coupling of hydrostatic and frictional pressure drops
- Final fluid positions

Foamed cementing techniques rely on the prediction of the density of foamed slurry based on the downhole pressures and temperatures. The slurry density at any point in the well will be determined by the pressure exerted on the slurry, the temperature at that point in the well, the volume of the base slurry, and the concentration of nitrogen.

Prior to the field execution of a foamed cement job, one can calculate the required nitrogen loading ratios based on the desired final fluid positions and foamed slurry densities or operation methods such as constant nitrogen rate, constant density, or “hybrid” (a combination of both).

Constant Nitrogen Ratio

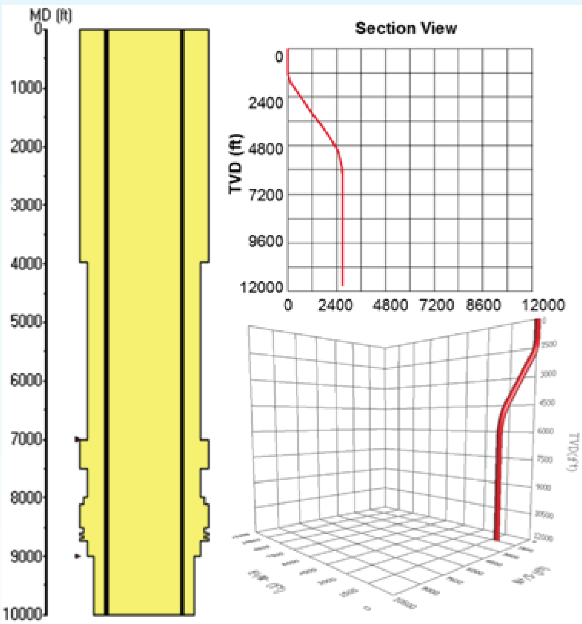
The nitrogen rate is held constant throughout the job. Thus, slurry density will increase as depth increases. Due to the density variation of the foamed cement column, it is sometimes difficult to consider both the well control issue at the top of the column and formation breakdown at the bottom.

Constant Density

This technique requires increasing the nitrogen flow rate as the slurry is pumped into the well. This results in a slurry column with a uniform density from top to bottom. In the field operation, the nitrogen rate is increased in increments for every 300~2,000 ft. of slurry, resulting in a slurry column with density steps. This technique is more popular for primary cementing application.

III. Case Study

To illustrate the computer modeling of foamed cement jobs, we use the following example.



Well location: Offshore with riser

Air gap (ft)	Water depth (ft)	Riser ID (in)
40.0	3500.0	16.000

Cased hole

#	Description	ID (in)	Top (ft)	Shoe (ft)
1	Previous	14.000	3983.3	7000.0

Open hole

#	Description	ID (in)	Bottom MD (ft)
1	Open hole	16.000	7500.0
2	Wash out	14.000	8000.0
3		15.000	8100.0
4		16.000	8500.0
5		15.000	8600.0
6		16.000	8649.9
7		15.000	8700.1
8		16.000	8750.0
9		14.000	9000.0
1		12.500	10000.0

Pipe:

#	Description	OD (in)	ID (in)	Length (ft)
1	Casing	9.800	9.000	10000.0

Fluid properties

#	Fluid	Density (ppg)	Model	PV (cP)	YP (lbf/100ft2)
1	Mud	9.40	BP	10.0	5.0
2	Cement	13.20	BP	18.0	8.0
3	Displacem	8.80	BP	10.0	5.0

Fig. 1. Wellbore Configuration and Fluid Data

The goal is to nitrify the cement slurry from its base density of 13.2 ppg [1581.6 kg/m3] to 12 ppg [1440 kg/m3]. This would require the top of the foam cement to reach 3280 ft [1000 m] from the surface.

Case 1: Design Mode - Constant Nitrogen Ratio

Using the above data and design mode with constant nitrogen ratio method, we ran the CEMPRO+ software and obtained the following results. This design assumes that only one nitrogen-loading ratio is used through the foamed cement slurry.

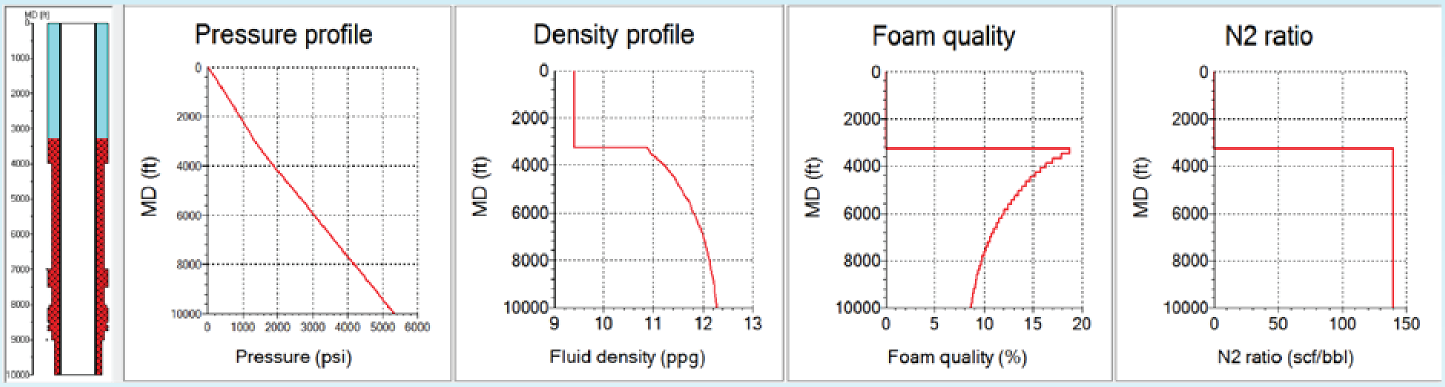


Fig. 2. Design Mode - Constant Nitrogen Ratio

Fig. 2 shows the pressure, density, foam quality profiles and the corresponding nitrogen loading ratio to achieve the goal. Due to the single nitrogen-loading ratio, we see a wide range of density and foam quality profiles as expected. Sometimes, the wide range of the foam quality profile may induce unstable foam on the top of the interval. The merit of the constant nitrogen ratio method is the simplicity of field operation: only one nitrogen ratio is required.

Case 2: Design Mode - Constant Density

If we further reduce the foam interval to 328 ft [100 m], we obtain very uniform distribution of density and foam quality profiles. This represents the constant density method. However, the operation requires 21 stages of nitrogen ratios, as shown in Fig. 3.

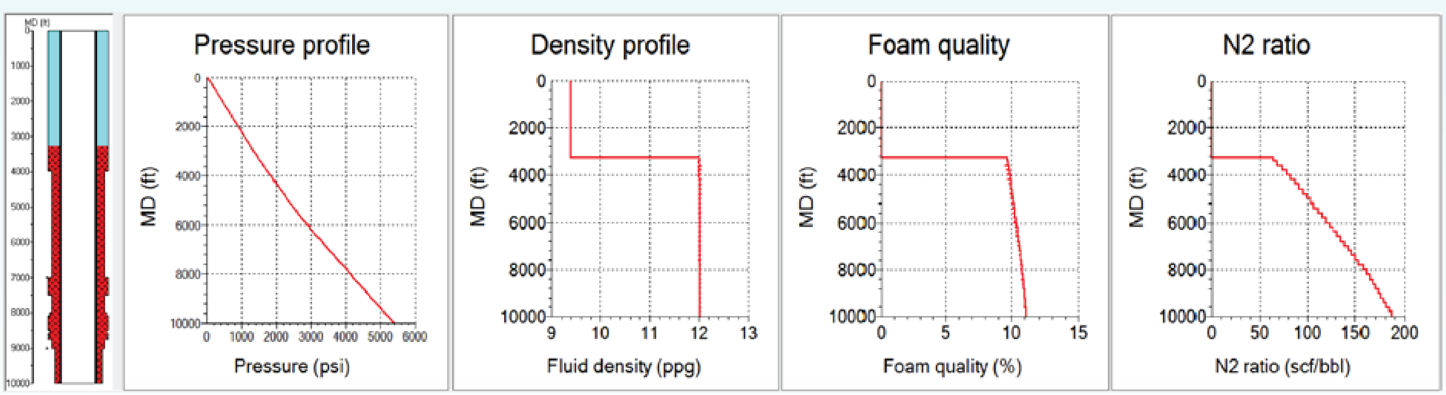


Fig. 3. Design Mode - Constant Density

Case 3: Design Mode - Hybrid Method

Now, we increase the nitrogen rate in increments for every 1312 ft [400 m] of slurry in annulus. This improves the profiles significantly with reasonably homogeneous density and foam quality profiles. Fig. 4 shows that the operation calls for 6 stages of nitrogen loading ratios.

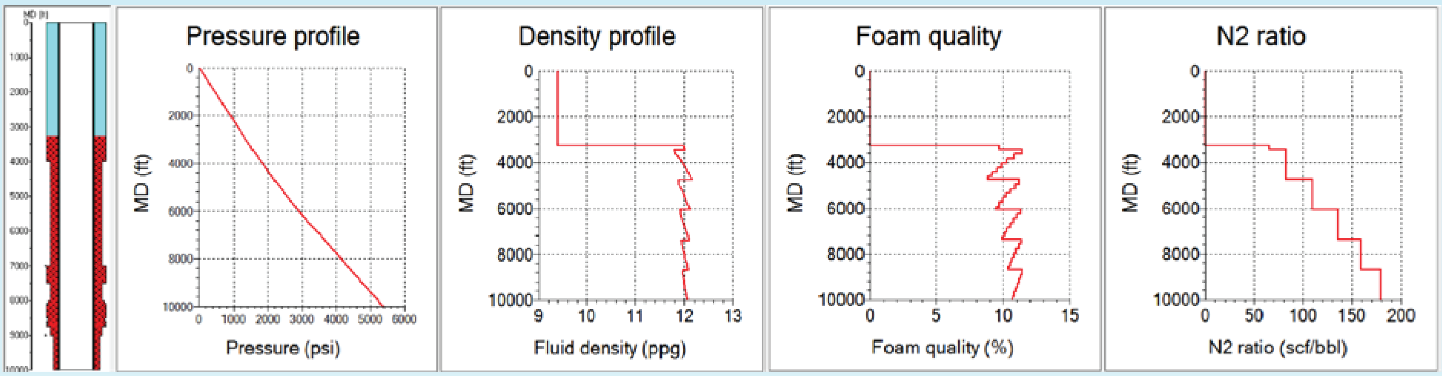


Fig. 4. Design Mode - Hybrid Method

Case 4: Dynamic Simulation

The results from the hybrid method will be used as a base to compare the static design mode and dynamic simulation.

With the designed nitrogen-loading ratio from the hybrid method, we then use them as the input for the dynamic simulation. The Fig. 5 shows the final fluid positions and density profile.

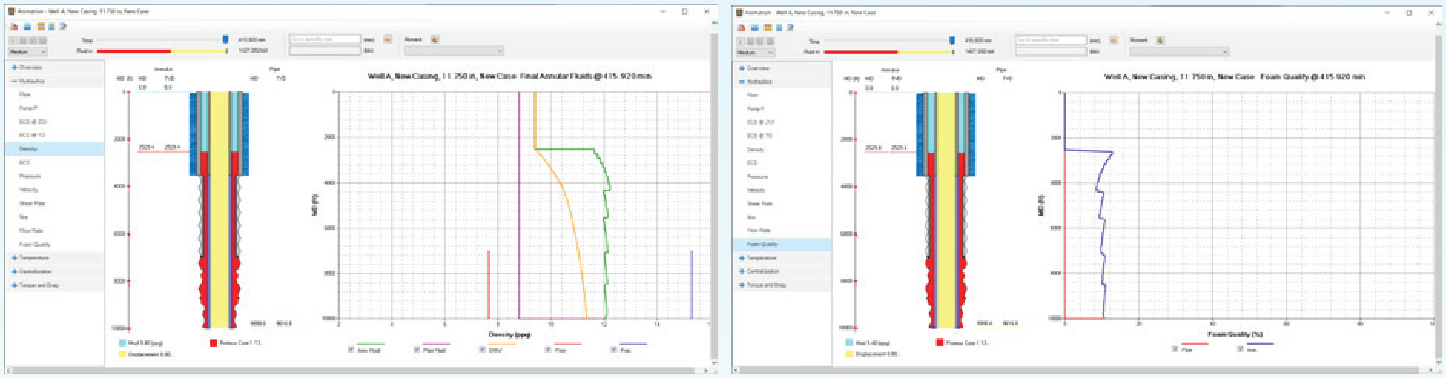


Fig. 5. Dynamic Simulation - Density and Foam Quality

The perplexing thing is that if one uses the nitrogen ratios calculated from design mode and perform displacement simulation, the final fluid positions are different from those of designed. In our case, the final foamed cement slurry is 3434 ft [1046.8 m], rather than 3280 ft [1000 m] as designed.

The reason is that in the design mode, the foamed slurry is assumed to be in its final position in the annulus at the very beginning. The calculation of required nitrogen loading ratio and base fluid volume ignores the frictional pressure losses, compression and expansion the foamed slurry undergoes during the displacement process.

However, during the displacement, the foamed slurry has to be first pumped down the casing string. Before it turns the corner, the foamed slurry is subject to the hydrostatic pressure exerted by the non-foamed fluids in the annulus.

Depending on the flow rates and fluid densities, the final fluid positions are different from those of designed using the (static) design mode. In other words, the final fluid positions, density and foam quality profiles are flow path dependent.

Fig. 6 shows the dynamic fluid density profiles as the foamed cement flows from inside casing into annulus. Note that the foam density and foam quality changes continuously as the foamed fluid undergoes compression downhole. The varying color red reflects the different nitrogen concentrations in the foamed slurry due to the combined efforts from:

- Multistage nitrogen injection ratios
- Increased pressure in depth
- Temperature increase

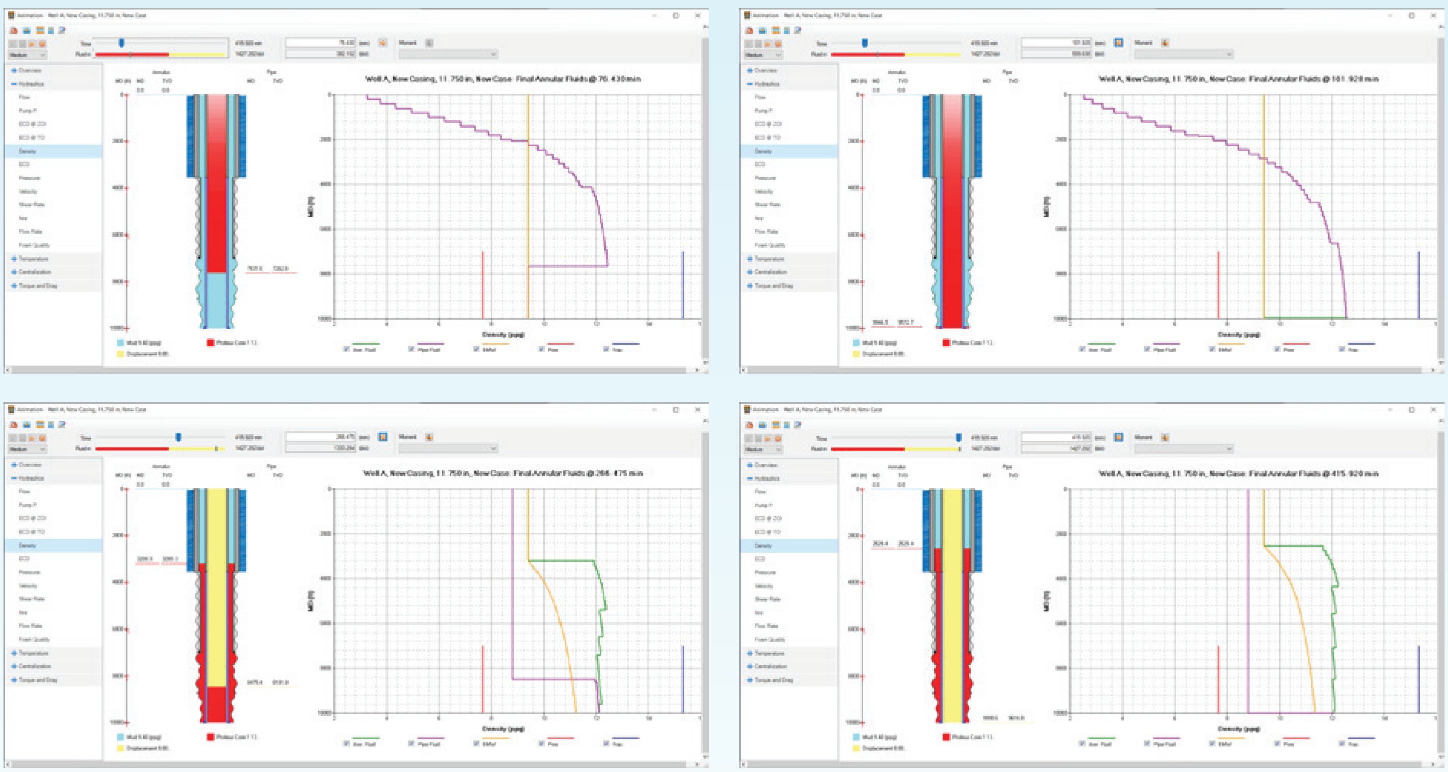


Fig. 6. Dynamic Simulation - Density Profiles

Unlike traditional cement jobs where flow rate is constant throughout the system at any given moment, the flow rate of foamed slurry is not. The downhole flow rate of foamed slurry is affected by the current pumping rate, the nitrogen loading ratio and the previous pumping stages. Numerical methods are employed to obtain volumetric flow rate along the flow path.

Fig. 7 illustrates the flow rates at the observation points (injection and annulus return) during the job.

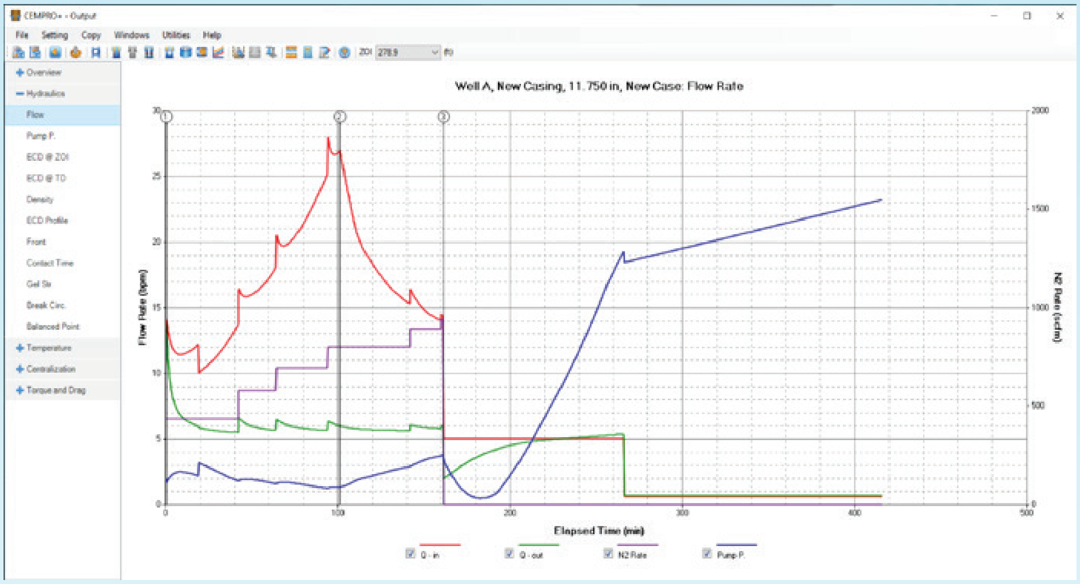


Fig. 7. Dynamic Simulation - Flow Rates

IV. Conclusion

Foamed cement is often considered as an alternative to conventional cement when lower slurry densities and moderate compressive strength are required. Foamed cement was first introduced in the early 1980s. Despite the numerous research and development projects on the dynamic phenomena associated with the compressible nitrified fluids, our understanding remains limited due to the following challenges:

(1) The Gap Between Lab and Downhole Condition

It is easy to measure the properties of foamed cement in lab, but properties like porosity, permeability, and strength change once it is pumped downhole. What happens to the slurry as it moves deeper into the well and annulus remains difficult to assess.

Efforts are being made to obtain and study samples of field-generated foamed cement from a specially designed sampling manifold.

(2) The Modeling Capacity

The nature of foamed cement makes predicting the behavior of compressible fluid very difficult. We have to first predict dynamic temperature profile and then use it to calculate the corrected foam quality. The same process also incorporates the frictional pressure calculation for foamed slurry.

A new computer model CEMPRO$^+$ addresses both the design and simulation issues of the foamed cementing operations. Incorporated into the model is an advanced algorithm that enables the software to handle up to 12 fluids (each fluid can be nitrified up to 50 stages), reverse circulation, variable choke pressures, etc.

This cement job simulator contributes to better understanding foam cement job designs and assures the isolation integrity of the structural casing strings for deepwater wells. The use of computer software for pre-job design and analysis has proven to be an effective way for improving the quality and success rate of primary cementing, especially when designing and executing foamed cement jobs.

For more information on CEMPRO$^+$, please contact Pegasus Vertex, Inc. at:

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