

Results of Laboratory Experiments to Simulate the Downhole Environment of Formation Testing While Drilling

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ABSTRACT

A laboratory-based experimental study was conducted to more completely understand the fundamentals of pressure transients produced by Formation Testing While Drilling (FTWD) equipment. These tools can be run in open hole, positioned at a desired level, and actuated to measure reservoir pressure and flow capacity while in a dynamic drilling environment. Any number of pressure measurements can be made at various levels. From these measurements, reservoir pressures can be accurately determined and formation mobility estimated. Sperry-sun*'s GeoTAP™ tool uses a testing technique in which a probe connected to a small sample chamber taps into a formation. Following connection, the small sample chamber is used for drawdown and build up tests.

In order to validate how accurately FTWD formation tools can determine characteristics of given hydrocarbon reservoirs, a comprehensive lab fixture was built to duplicate the downhole environment. This fixture includes the capability to circulate mud and form a mud cake on a core, to control hydrostatic mud and formation pressures, and to perform a pressure test. The pressure test produces a transient using exactly the same pad, transducers, electronic control board and software used in the current GeoTAP tool.

The fixture was run repeatedly for a wide range of simulated downhole conditions by varying formation pressures, hydrostatic overbalance, flow rate, flow line volume, and pretest chamber volume; and using different cores and reservoir fluids. The permeability of the different cores was analyzed according to the experimental results from the fixture, using an analytical spherical-flow equation model.

The validity of experiments was initially assessed using a single-phase spherical flow analytical model. To study multiphase invasion effects, the UTCHEM** mud infiltrate simulator was used to estimate the extent of the invasion. Results from UTCHEM were then used as initial conditions for a multiphase transient analysis. In this step a commercial reservoir simulator, Landmark*'s VIP, was used to determine the transient

response considering the invaded region in the vicinity of the near wellbore. When these more powerful numerical simulators were used, the match between experimental data and theoretically expected results was better than 90%.

INTRODUCTION

Modern technology has advanced in enabling us to perform a pressure transient test while in a dynamic drilling environment. These Formation Testing While Drilling tools have been used to measure reservoir pressures and to obtain local permeability. Most FTWD tools have a hydraulically activated pad that goes downhole in the retracted position. The tool is positioned at the desired level and the pad is extended. Extension causes a small circular packer to seal against the mud cake on one side of the hole. A metal snorkel tube positioned in the center of the packer is then forced through the mud cake into the formation. To ensure good hydraulic contact of the probe with the porous medium, it is customary to rapidly withdraw a small volume of fluid. During this high-rate withdrawal, pressure is recorded to produce a pressure transient drawdown and buildup data.

Very little laboratory work associated with pressure transients in formation testers has been published. Considering the pervasive use of these tools in the oil industry, surprisingly, there is only one known pressure transient test conducted with an actual mud system or mud cake (see Desbrandes and Xu, 1994). However these experiments were performed in only a few cases and with very low permeabilities and formation pressures less than 600 psi. None were conducted in the high pressure or high permeability range.

In view of the need for testing the capability and design of FTWD tools, an experimental fixture was constructed that could simulate the action of the GeoTAP tool under simulated field conditions.

After an experiment has been performed, permeability of the core is calculated using the analytical spherical solution installed in the real-time software module of the tool. The study is then concluded by comparing the test data with simulation results based on a mud invasion model and a multiphase numerical model for determining permeability.

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EXPERIMENTAL APPARATUS

In this study, an experimental apparatus was designed to analyze pressure transients recorded by the GeoTAP tool. The schematic diagram of the total system is shown in **Fig. 1**. As shown in that figure, the experimental apparatus is composed of the core holder, three cylinders, three pumps, the drawdown piston, two transducers, three solenoids, and an electrical control and visualization system.

The core holder includes an outer housing, a space for core, and a probe section. The outer housing holds a core that represents the formation. The housing is connected to the cylinder filled with oil with apparent viscosity representative of formation fluid. Oil is continually injected through the core by a pump and is maintained at a constant pressure to duplicate the reservoir pressure. The probe section consists of a rubber pad, a snorkel, and a filter, all of which are the same as parts used in formation testing while drilling tools.

Mudcake is formed on the surface of the core by circulating mud from the mud chambers. The mud used in our experiments is the typical 12 lb/gal water-based mud. A timer controls circulation, and the direction of flow is changed as mud is deposited. The thickness of the mudcake is considered to be sufficient when the pressure readings indicate that an adequate overbalance can be maintained. The thickness of the mudcake can also be measured through an access port on the fixture.

After adequately thick mudcake is formed, circulation is stopped; and constant pressure is maintained by the cylinder side pump to represent the hydrostatic overbalance of downhole conditions.

Both hydrostatic and formation pressures are maintained by an accurate, point-operating relief valve attached to the pumps. Two transducers are attached; one on the formation side and the other on the flowline side sending pressure recordings to a control module that converts the analog signals to digital signals. Pressure recordings are shown on a computer, using custom-made, real-time Graphical User Interface (GUI) software.

For the drawdown and buildup tests, the drawdown piston is controlled by three accumulators that are controlled internally by three solenoid valves. Electrical signals can open or close the valves and give orders to the system to extend and retract the probe and to drawdown. These accumulators are attached to the solenoids and are powered by the system pump. All the experimental procedures are controlled by a motherboard that is connected to the computer. Additionally, high pressure accumulators smooth the flow and maintain steady and constant pressures. The whole

system is built to withstand high pressures of up to 6,000 psi.

EXPERIMENTAL PROCEDURE AND RESULTS

A typical pressure recording during a test is shown in **Fig. 2**. The hydrostatic pressure of the mud (P_{hydr}) is measured at the beginning on the left of **Fig. 2**. The term t_{set} is the time to set the probe against the mud cake, t_{start} is the start of the pretest, and t_{dd} is the end of the flow period.

The buildup operation proceeds until it reaches the formation pressure. The term t_{stop} refers to the end of the shut-in and the pressure returns to the hydrostatic mud pressure. t_{final} is the end of the test and the probe is retracted. The pretest phase indicates whether a good seal to the formation has been affected or if the probe is tending to plug or if the formation is completely tight. Also the effects of clean up, of insufficient build up time in low permeability cores and of the appropriateness of the pump rate can be examined. Once the experiment data indicate a feasible experimental setup, the properties were changed and the tests run again.

To test the fixture in various mobility cases, three kinds of cores with different permeabilities (982 md, 1946 md and 3649 md) were used with two different viscosities (10 cp and 100 cp) for formation oils to produce eight different mobility ratios (k/μ , md/cp). In order to test the accuracy and applicability of the tool design, the pretest volumes were varied from 3cc, 5cc to 10cc. Also, the flow line volumes were changed at every experiment to 100 cc and then 50 cc to examine the flow line storage effect. Different drawdown flow rates were performed at 1 cc/sec and 0.5 cc/sec to test the appropriateness of the flow rates for different permeabilities. The tests were analyzed at low (500 psi) and high formation pressure (1500, 2000 psi) with overbalance pressure differences of 500 and 1000 psi to obtain a still broader range of experimental data. Wide ranges of testing conditions were studied, and there were a total of 180 experiments.

Once an experiment is completed, the data is initially analyzed by an analytical single phase spherical flow solution introduced by Proett and Chin (1998). Based on this theory, the permeability of the formation is initially calculated. This method of analysis is also used in the field for a preliminary calculation of permeability without prior knowledge of a formation.

Five representative cases were selected for this experimental study. Each case is described in Table 1. **Figs. 3 to 7** show the experimental data along with the synthetic curve based on the analytical spherical model. In these figures, the bold line represents experimental data, and the dots identify the spherical solution curve

for drawdown and build up. The dashed line is the pressure reading from the formation pressure side transducer indicating whether a constant formation pressure was maintained during the test. Table 2 lists results for each case of the test. The permeability calculated with the spherical flow equation indicates a fair match with the actual core permeability.

THEORY OF OPERATION

A pressure drawdown is conducted by withdrawing a small amount of fluid from the formation at a known rate through the snorkel during the pretest. The combination of the snorkel diameter and the flow rate determines an effective range of operation. The maximum drawdown pressure pulse can be determined from the spherical flow equation from Proett and Chin (1998). Here ΔP_{dd} is the final drawdown pressure differential at time $t=\infty$, given by

$$\Delta P_{dd} = (14,696) \left(\frac{q_{dd} \tau_p \mu}{2\pi r_p k_f} \right) \quad (1)$$

In equation (1), k_f is the formation spherical permeability (md), μ is the fluid viscosity (cp), r_p is the probe radius (cm), τ_p is the probe geometric shape factor (1-1.50), and q_{dd} is the drawdown flow rate (cc/sec).

With 0.5 cc/sec and 1 cc/sec drawdown flow rates and a 1.0 cm probe, it is possible to test formations ranging from 0.5 to 4000 md with pressure differentials ranging from 2 to 5000 psi. The external elastomeric seal was designed to withstand a drawdown pressure of 5000 psi for up to 100 pressure cycles.

Previously published works from Proett et. al. (1996, 1998) show the development of an exact solution for the spherical flow equation that governs the pressure transients for probe type tools. Previous work has also demonstrated that a subset of this exact solution can be used to characterize Formation Testing While Drilling tools. This simpler solution consists of an exponential decay function where the buildup and drawdown curves can be expressed as follows

$$P_{bu}(t) = P_f - \beta e^{-\frac{t}{\alpha}} \quad (2)$$

and

$$P_{dd}(t) = P_{set} - \left(\frac{P_{set} - P_{dd}}{1 - e^{-\frac{-\Delta t_{dd}}{\alpha}}} \right) \left(1 - e^{-\frac{t'}{\alpha}} \right) \quad (3)$$

where t' is the drawdown time ($T - t_{start}$) and t is the buildup time ($T - t_{dd}$).

From these equations, it is possible to perform a regression analysis to determine the projected formation pressure P_f , the buildup magnitude β , and the time constant α . Using these constants, a synthetic curve can be produced with Eqs. (2) and (3). By comparing the recorded data points to the curve points at the same time, a standard deviation σ is determined. Then the synthetic curve can be plotted along with the actual data on a computer monitor. The visual display plus the standard deviation of the data against the synthetic curve provides an enhanced and reliable method for evaluating the pressure test.

The transient parameters are related to spherical formation permeability, k_f , and flowline fluid compressibility, c_{fl} . The parameters α and β are used to determine the permeability, assuming a viscosity μ . Then the time constant α is used to determine the flowline fluid compressibility as follows

$$k_f = 14,696 \frac{\mu}{\beta} \frac{q_{dd} \tau_p}{2\pi r_p} \left(1 - e^{-\frac{-\Delta t_{dd}}{\alpha}} \right) \quad (4)$$

and

$$c_{fl} = \frac{\alpha k_f 4\pi r_p}{14,696 \mu V_{fl} \tau_p} \quad (5)$$

where V_{fl} is the flowline volume.

VALIDATION FOR EXPERIMENTAL RESULTS

Because water-based mud was used, water invaded the core prior to and during testing. Accordingly, several cases — with lower viscous fluid owing to the presence of water — showed a lower permeability based on the single phase analytical solution than the actual core permeability. For example, for the two simulation cases described in **Table 3**, the permeability calculated with one-phase spherical flow equation were 350 and 472 md respectively. The predicted permeabilities are lower than that of the actual core value (982 md).

Therefore, a more accurate oil-water multi-phase flow numerical simulation had to be used to consider the effects of mud invasion on the experiments. Such an advanced computational simulation was possible because the rock, fluid, mud properties, and formation pressures were accurately determined from core tests (See **Fig. 8**).

For the two simulation cases given in Table 3, UTCHEM's mud invasion was introduced to simulate the process of mud-filtrate invasion. The simulation includes a mud cake growth model that is coupled to the invasion process. Recent studies on the use of this

simulator are well described by Wu et al. (2001, 2002). After a dynamic mud infiltration flow rate is determined, this information is used as input value for the reservoir simulator. The results from the experimental fixture were validated using a full 3D commercial multiphase fluid flow reservoir simulator (VIP). This simulator can precisely reproduce near wellbore effects related to probe and the sealing packer.

Input parameters for UTCHEM and VIP are listed in **Table 4**. Also, the input data for the relative permeability of the manufactured core is plotted in **Fig. 8**. In addition, the graphical rendering of the 3-D finite difference grid to simulate the tool's geometry, the surface of the probe, and the surrounding borehole and rock formation is shown in **Fig. 9**.

The numerical simulation results, taking into account mud cake invasion and multi-phase flow, are plotted in **Figs. 10 and 11**. They show more than 90 % agreement between the numerically simulated model and the measured experimental data. Therefore, for fluid flow of low viscosity and high permeability, it might be safer to consider the process of mud infiltrate invasion for the calculation for mobility.

CONCLUSIONS

A laboratory scale experiment was developed to study pressure transient analysis in a simulated downhole environment. This work has important applications for the use of formation testing while drilling tools where invasion could be more dynamic than experienced with traditional wire line tools.

Pressure tests were conducted with actual mud cake to assure the similarity with downhole conditions. In addition, the experimental apparatus was designed to endure pressures up to 5,000 psi. An extensive amount of data was gathered by changing various parameters for a wider range of results in order to improve the tools and to evaluate various theoretical models.

A single phase spherical solution was used to invert the pressure transient data and to determine the permeability and compressibility. Results closely matched the rock-core laboratory measurements. However, to determine the effects of multi-phase invasion, a full-scale 3D simulation was performed. The mud invasion profile was modeled using UTCHEM. Results from UTCHEM were applied as initial conditions for the 3D transient pressure simulation performed using VIP. The results closely match the experimental data when using relative permeabilities derived from rock-core measurements. These simulations demonstrated the accuracy to which the experimental study represented the downhole environment experienced by FTWD tools. The simulations and the experimental study also showed

permeabilities can be reliably determined using FTWD tools over a wide range of operating conditions using an analog single-phase spherical flow solution. In addition, for cases of high permeability and low fluid viscosity, the study showed that multi-phase flow analysis should be considered for a more refined interpretation of the measurements

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fluid flow analysis methods. He has served on the SPWLA and SPE technical committees and served as the Chairman for the SPE Pressure Transient Testing Committee.

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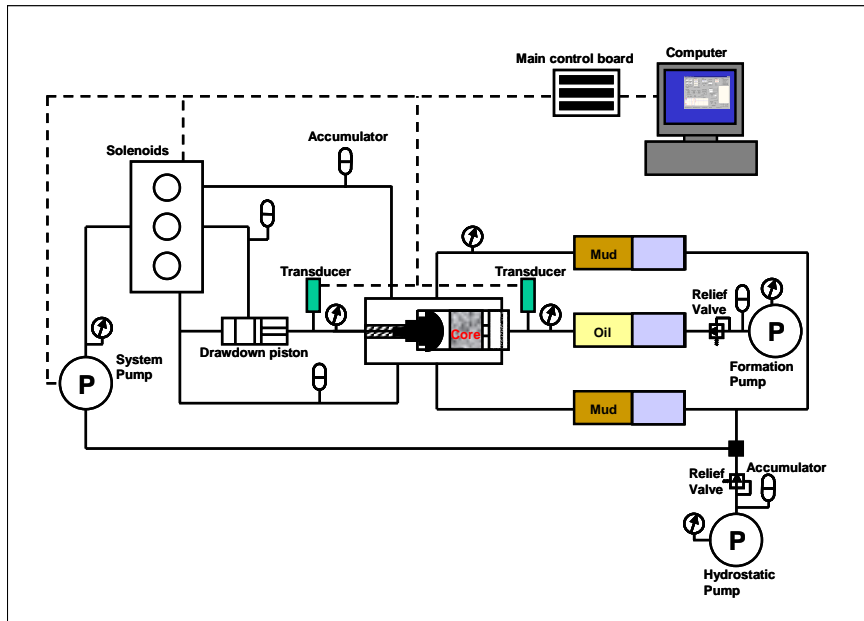


Fig.1. Schematic description of the FTWD experimental fixture.

FACTOR	Case 1	Case 2	Case 3	Case 4	Case 5
Permeability (md)	982	982	982	1946	3649
Viscosity (cp)	10	100	100	100	100
Drawdown Flow rate(cc/sec)	1	1	0.5	1	1
Flowline Volume(cc)	100	50	100	100	100
Pretest Volume(cc)	3	3	10	5	10
Hydrostatic/Formation Pressures (psi)	1000/500	1000/500	2500/1500	2500/1500	2500/1500

Table 1. Case description for the experimental data.

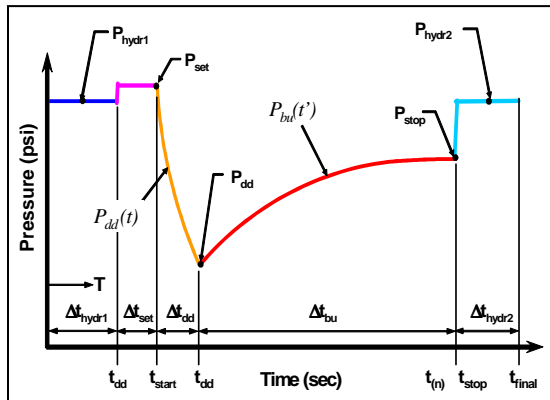


Fig. 2. Typical formation tester pressure recording sequence during operation.

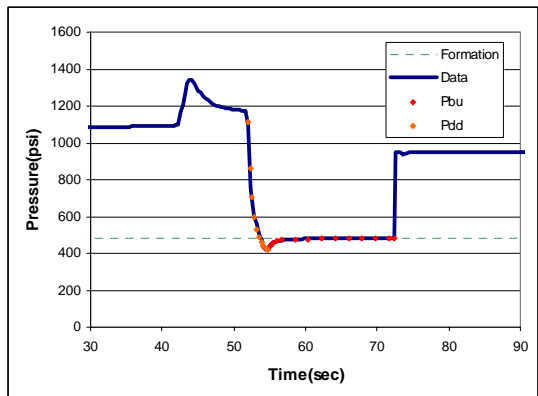


Fig.3. Experiment data results with the synthetic curve for Case 1.

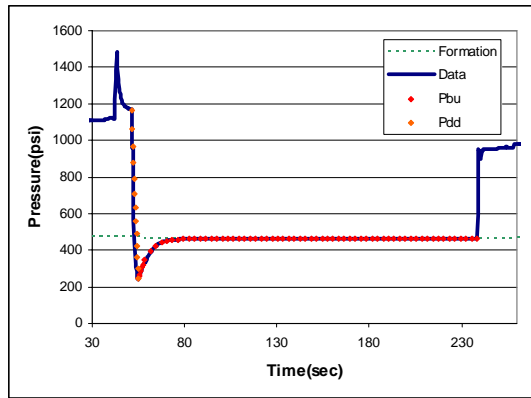


Fig.4. Experiment data results with the synthetic curve for Case 2.

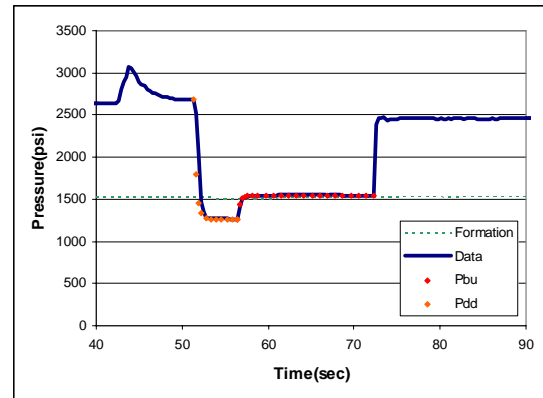


Fig.6. Experiment data results with the synthetic curve for Case 4.

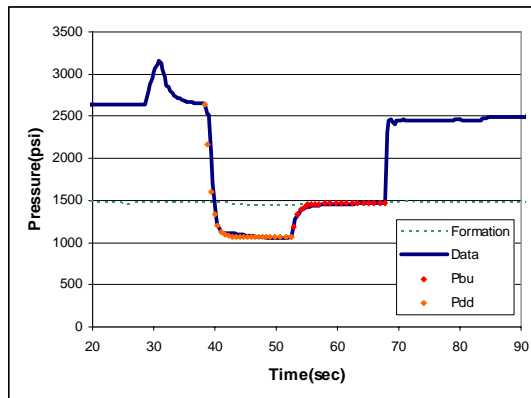


Fig.5. Experiment data results with the synthetic curve for Case 3.

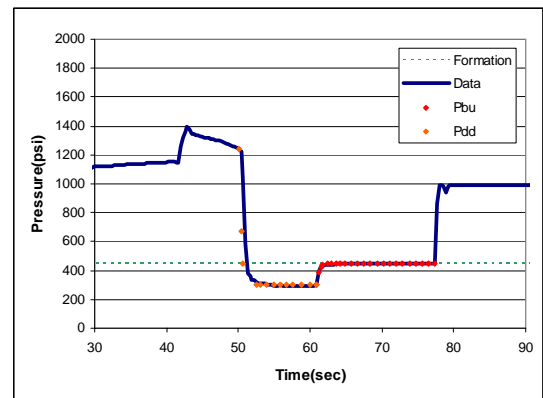


Fig.7. Experiment data results with the synthetic curve for Case 5.

Data	Case 1	Case 2	Case 3	Case 4	Case 5	Experimental Event	Description
P_{hyd1}	1092	1108	2634	2624	2611	Start of test sequence	Initial hydrostatic(psi)
P_{set}	1170	1167	2647	2679	2616	Initiating a drawdown	Probe setting pressure(psi)
P_{dd}	423	246	1068	1262	1355	At least 10 second after tdd or at end of drawdown	Drawdown pressure(psi)
P_{stop}	478	462	1463	1545	1514	Last buildup pressure	Stop pressure(psi)
P_{hyd2}	949	1023	2576	2551	2505	End of test sequence	Final hydrostatic(psi)
Δt_{dd}	2.87	3.6	14.1	5.1	10.8	Drawdown time period	Drawdown time(sec)
Δt_{bu}	17.63	183.3	15.3	39.9	16.2	Buildup time period	Buildup time(sec)
α	0.72	5.42	0.83	0.30	0.57	Buildup time constant	67% of buildup
β	54.98	216.16	394.49	283.0	158.83	Buildup magnitude	Differential pressure ($P_r - P_{dd}$)
P_f	478	462	1462	1545	1514	Formation pressure	Formation pressure from curve fit(psi)
σ	1.14	0.5	1.05	1.3	0.86	Standard deviation	Curve fit quality
k_{cal}	1094	1069	1030	1985	3354	Permeability calculated	Calculated permeability(md)
k_{core}	982	982	982	1946	3649	Measured permeability of the core	permeability of core(md)

Table 2. Selected Data and permeability results for spherical solution.

FACTOR	Simulation 1	Simulation 2
Permeability (md)	982	982
Viscosity (cp)	10	10
Drawdown Flowrate(cc/sec)	1	0.5
Flowline Volume(cc)	50	100
Pretest Volume(cc)	10	3
Hydrostatic/Formation Pressures (psi)	1000/500	2500/1500

Table 3. Case description for numerical simulation study

FACTOR	Simulation 1	Simulation 2
Mudcake Permeability(md)	0.01	0.01
Mudcake Porosity	0.4	0.4
Mud Solid Fraction	0.5	0.5
Water viscosity(cp)	1	1
Total invasion time(hrs)	4.5	8
Maximum cake thickness(cm)	2	2

Table 4. Mud input properties for numerical simulation

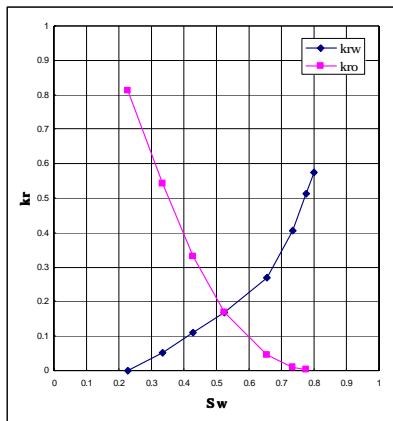


Fig. 8. Reported relative permeability curves for 982 md core

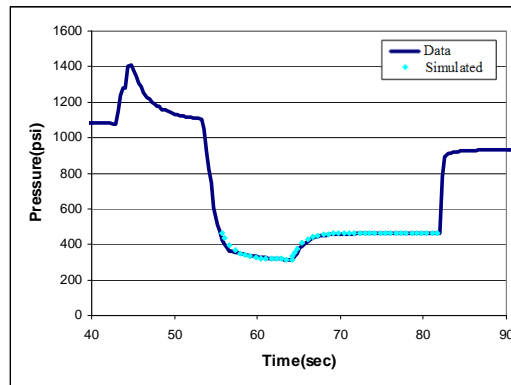


Fig.10. Comparison of the experimental data plot with the numerical simulation obtained by UTCHEM and VIP of Simulation 1.

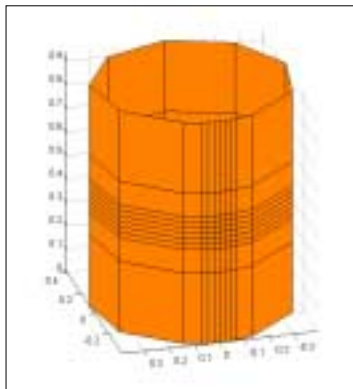


Fig. 9. Graphical scheme of the 3D finite-difference grid for validation.

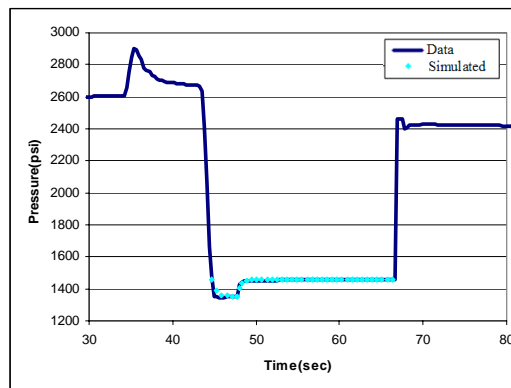


Fig.11. Comparison of the experimental data plot with the numerical simulation obtained by UTCHEM and VIP of Simulation 2.