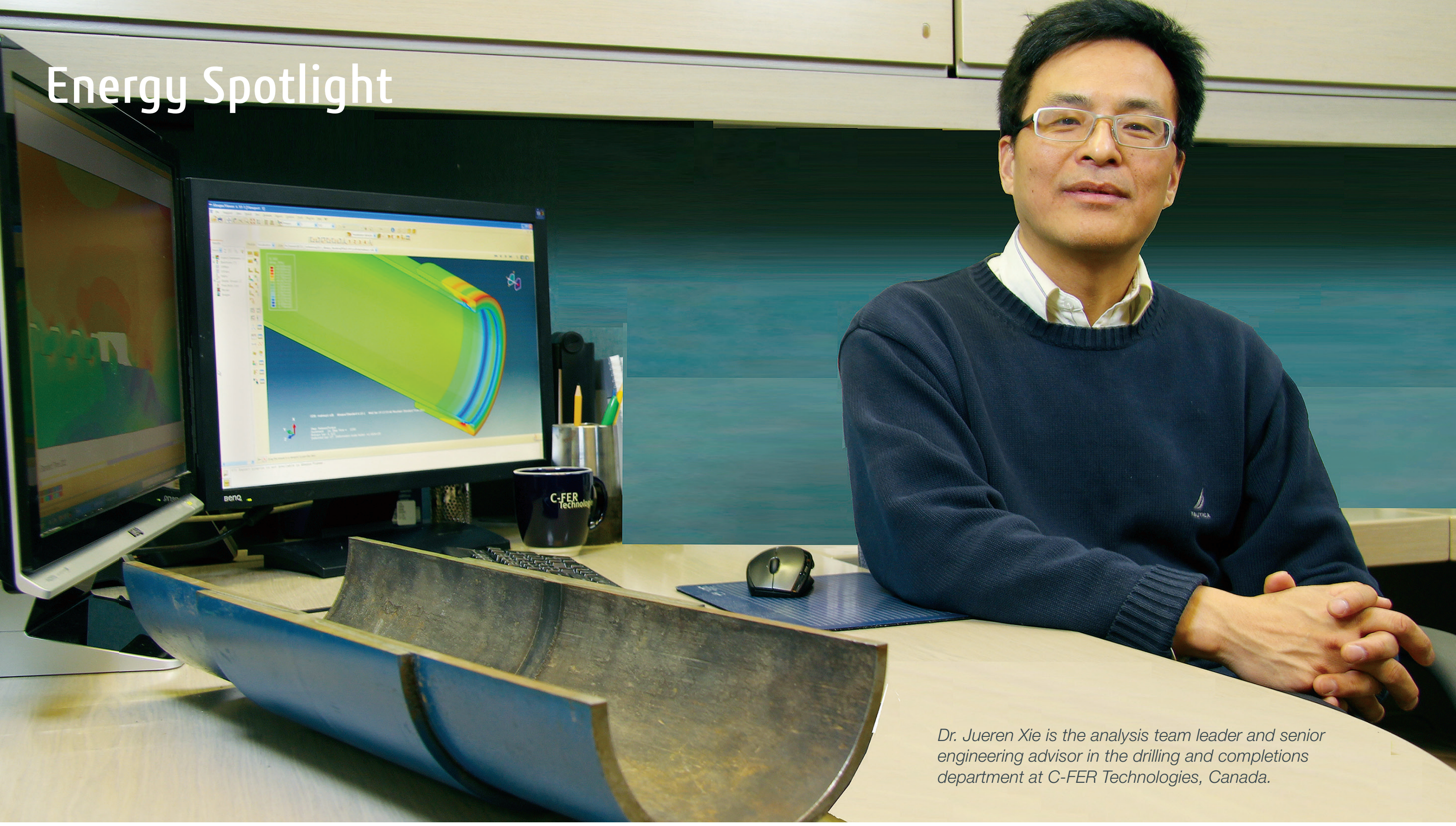

Dr. Jueren Xie is the analysis team leader and senior engineering advisor in the drilling and completions department at C-FER Technologies, Canada.

Simulating the Physical Challenges of "Unconventional Oil"

Abaqus accurately predicts realistic performance of well designs in challenging oilfield applications

Commercial oil drilling has become far more complicated since the day in 1859 when Edwin Drake struck oil in Titusville, Pennsylvania at a depth of 69 1/2 feet. Yet even back then, drilling faced technical challenges. Drake's team needed a way to hold back collapsing earth and water. They solved the problem by drilling inside a cast iron pipe—a forerunner of modern drilling equipment and well casings.

It has been a long time since companies struck oil regularly at such shallow depths. These days the wells are deeper, the well locations less accessible, and the oil heavier or otherwise more difficult to extract. All of this has led to the development and testing of a host of technologies needed to reach, and recover, what is now called "unconventional oil."

Many of these technologies have been explored and improved upon by C-FER Technologies Inc. (C-FER). Originally the Centre for Frontier Engineering Research, it was founded in the 1980s as an industry-directed engineering, testing, and applied research center to solve problems posed in constructing and maintaining offshore and Arctic structures in Canada. In the 1990s, C-FER formed a wholly owned subsidiary, C-FER Technologies Inc., to bring its advanced engineering and testing services to the marketplace on a competitive, commercial basis.

Abaqus well suited for oil well performance analyses

Today C-FER's structural, mechanical, petroleum, and reliability engineers conduct applied research and development, perform full-scale testing, and provide engineering consulting for the upstream oil and gas, and pipeline transmission industries, as well as other industries. "We have a longstanding tradition of rigorous physical testing for products," says Dr. Jueren Xie, senior engineering advisor for C-FER, "but we have nearly as long a history with computer-aided engineering (CAE) tools."

From the beginning, Finite Element Analysis (FEA) software has been an important tool at C-FER. In 1994, as the company's FEA services met with increasing demand, they adopted Abaqus FEA software from SIMULIA, the Dassault Systèmes brand for realistic simulation. Projects conducted by C-FER using Abaqus include design of full-scale tests, failure investigation, and design optimization.

"Proving out technologies for unconventional oil wells with Abaqus has long been one of C-FER's most important tasks," says Xie. Unconventional oil and gas typically refers to resources such as oil sands, heavy oil, oil and tight gas shales, deep and deep-sea reservoirs, and Arctic reservoirs located below thick layers of permafrost. "These wells frequently involve ancillary extraction technologies that place considerable loads on the wellbore equipments," Xie notes.

For example, thermal well technologies, such as Cyclic Steam Stimulation (CSS), with peak temperatures higher than 330°C, and Steam Assisted Gravity Drainage (SAGD), with peak temperatures higher than 220°C, have been widely used to produce viscous heavy oil and bitumen. Many of these applications use large diameter wells with complex three-dimensional trajectories to reach the target reservoirs.

The high temperature and/or high pressure often cause significant formation loading from the interaction of the wellbore equipment with the surrounding formation. This can potentially induce large deformations and changes in the material properties, causing well mechanical failures, such as buckling, shear, and collapse; casing connection failures from parting or fluid-leaking; cement functional failures (cracking and the formation of fluid flow paths); horizontal well failures due to structural damage; serviceability failures (wellbore access and sand control); and in rare instances, wellbore leakage and blowout events.

Since the traditional stress-based design criteria used for conventional wells no longer apply, C-FER developed a strain-based design concept for designing unconventional wells. Incorporating initial well-completion designs and operational and field conditions, C-FER evaluates projects using both full-scale physical tests and numerical simulations. "Because such physical testing is generally costly, especially for qualification testing under a wide range of load scenarios, it is more economical and efficient to evaluate early-stage designs with FEA," says Xie.

Two recent examples where C-FER has used Abaqus to optimize wellbore designs in unconventional applications include coupled thermal-mechanical analysis of wellbore production and optimization of casing and slotted liner designs. "Both of these applications involve highly nonlinear response of wellbore equipments to production loads," Xie notes, "and in both cases, Abaqus helped to determine the realistic load response, and to evaluate whether or not the field equipment would perform properly for the life of the well."

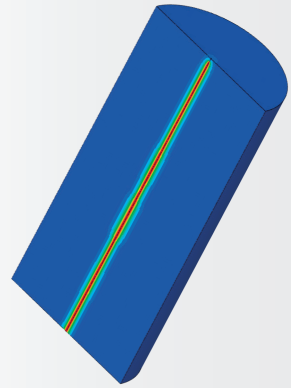

Figure 1. Simulation of a thermal well production showed significant temperature gradient from well center, suggesting high potential for cement cracking during heating (red for the high temperature, and blue for the ambient temperature).

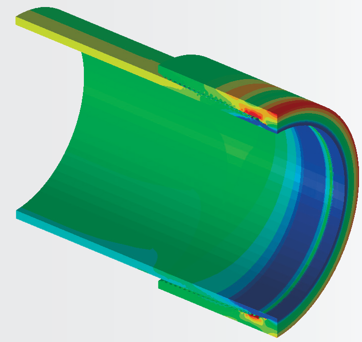

Figure 2. Simulation of a premium connection under curvature loading showed that the critical threads in the connection would experience alternating tensile (red) and compressive (blue) axial strain, causing potential connection fatigue failure under casing rotation loading.

Case 1: Coupled Thermal-Mechanical Analysis of Wellbore Production

One of the key design loads for unconventional wells is the formation loading resulting from well production. Determination of formation loads has been difficult and challenging, as it is often a result of multiphysics effects involving fluid, thermal, and structural relationships. Modeling of unconventional well production often requires four sequential technical evaluations: wellbore heat transfer, geothermal, geomechanical and soil deformation, and casing/cement/formation interaction analyses.

Based on years of modeling experience in the area, C-FER has developed a unique assessment method for unconventional wells involving the use of coupled thermal-mechanical numerical modeling methods. This approach allows for the modeling of heating transfer, soil deformation, and well response behavior in one structural model that includes the well casing, and cement and formation components. "Abaqus offers a large collection of constitutive material models that allow us to properly model the nonlinear response of the casing/cement/formation system in unconventional wells," notes Xie.

A recent C-FER project studied the impact of heating rate on well cement integrity for SAGD wells placed at a total vertical depth (TVD) of 400 m and an operating peak temperature of 220°C. Cement integrity becomes a challenge for the initial heating stage of the wells due to the potential of developing radial cracks as a result of the rapid thermal expansion of the casing, which imposes high tensile circumferential stresses in the cement sheath.

The numerical analysis demonstrated that at a typical heating rate of 0.6°C/min on casing internal surface (i.e. about 6 hours to reach a peak temperature of 220°C), the cement sheath over the entire well depth would experience significant cracking, potentially compromising the primary function of the cement sheath hydraulic (see Figure 1).

However, the analysis also showed that heating rates slower than 0.6°C/min appeared to mitigate this cracking potential because slower heating rates allow sufficient heat to be transmitted to formation, such that the outer surface of the cement and near wellbore formation expanded resulting in more confinement to the wellbore. As a result, the coupled analysis showed that slow heating rates would lead to less potential damage to the cement.

While it is recognized that the use of a low thermal conductivity cement would generally improve the thermal efficiency over the life of these wells, Abaqus analyses also showed that even slower heating rates (and perhaps cooling rates) should be used to maintain cement integrity in wells with low thermal conductivity cements.

C-FER has also performed several projects using the coupled thermal-mechanical analyses to study the impact of thaw subsidence on well casing integrity for Arctic applications. The results from the coupled analysis include formation property changes and formation movements (e.g. subsidence and shear) as a function of well production and formation thaw. These results are then used to assess potential casing deformation (i.e. buckling and shear) with the casing modeled using beam elements and the soil represented by a series of spring elements. A new multiphysics analysis capability recently implemented in Abaqus allows for concurrent heat transfer and soil deformation in porous media on fluid phase change analyses to be performed in a single, fully coupled model with the capability of capturing the effects from iced to thawed conditions. This is anticipated to be of use in these situations where the combined effects should be examined as the thaw subsidence zone evolves.

Case 2: Optimization of Casing and Liner Designs for Thermal Wells

Over the last twenty years, C-FER has performed numerous projects on analysis of oil well equipments for oil operator, vendor, and consulting companies. In many instances C-FER used FEA methods to assess and optimize the casing and liner designs for thermal well applications.

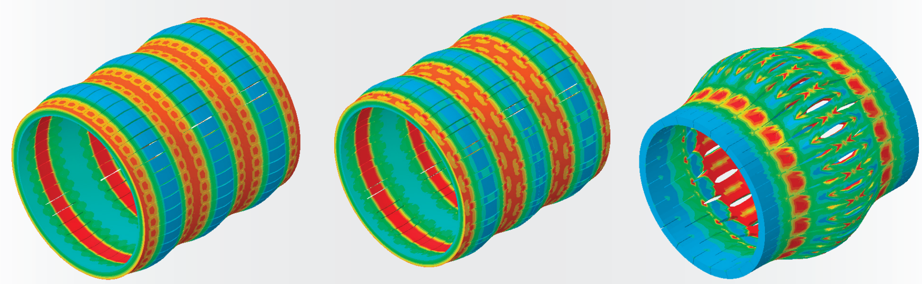

Figure 3. Simulation of slotted liners revealed that the staggered (left) and gang (center) slot patterns had sufficient axial strain absorption capacities, while the overlapping (right) slot pattern had limited strain capacity by exhibiting "birdcaging" deformation mode, compromising the sand control functionality (red for high plastic strains).

Oil and gas industry studies have found that connection failures account for 85 to 95 percent of all oilfield tubular failures. As such, analysis of casing strings for these thermal wells has often focused on assessing the structural integrity and sealability of connections. One area related to casing connections in thermal wells recently examined by C-FER was the combined mechanical-thermal cycle fatigue life. During the construction of thermal recovery wells, it is common to rotate the casing string (assembled length of linked steel pipe sections) for primary cementing. This removes any fluids used to drill the well and improves cement bonding and isolation, but it also causes potential connection fatigue damage due to cyclic bending in the curved or build sections of the wells. "It's important to know how much the casing rotation during well construction and the resulting stress/strain variations during cementing increases the risk of connection failure during the subsequent thermal recovery operations," Xie says.

Engineers at C-FER performed nonlinear structural analyses with Abaqus to predict fatigue life in the connection after the applied rotations during cementing and the subsequent thermal cycles. They created a 3D computer model for the "premium" casing connection design to enable the analysis of an initially axisymmetric structure subjected to the nonlinear, non-axisymmetric deformations associated with the bending rotation of the casing. For the scenario examined, the analysis results suggested that a 244 mm connection design could tolerate several hundred thermal cycles with the casing rotation (in a well with up to 12°/30 m curvature) and a somewhat larger number of thermal cycles without (see Figure 2).

In the case of formation induced cyclic shear loading, the analyses showed that the connection design could endure about one-fifth the number of thermal cycles with casing rotation and only about 8% more thermal shear cycles without. "The results clearly showed that cyclic formation shear loading was much more critical than thermal cycle loading," Xie points out. For the scenario examined, the analyses also established that casing rotation had only a modest impact on fatigue life of the connection design. Giving support to the results, the predictions showed good agreement with physical test results published for connections of the same size and similar design.

Another area where C-FER has conducted similar assessments is the optimization of horizontal liner design for SAGD wells. Many of the heavy oil reservoirs where SAGD is applied are highly unconsolidated, and therefore both the steam injection and horizontal wells need some form of sand control, such as slotted liners or wire-wrapped screens. "C-FER has conducted assessments for several operator and vendor companies through evaluation of a number of design scenarios to identify designs which optimized the Open Flow Area (OFA), while providing the required sand control and structural functions of these liners," Xie says. In these projects, C-FER used Abaqus to create 3D solid models to identify liner design variants that delivered the required structural and service functionality of the application.

As an illustrative example of the slotted liner evaluation, C-FER used Abaqus to assess the effect of slot pattern designs, which included staggered slots (evenly spaced repeated slot column), gang slots (ganged repeated slot column), and overlapping slots (evenly spaced overlapping slots). The analysis revealed that the staggered and gang slot patterns had sufficient structural capacity for the anticipated installation and operation loads of the scenarios, if OFA was 3% or less. However, the assessment showed that the overlapping slot pattern had limited structural capacity to absorb the thermal strains and to sustain the external formation pressures of the application. For example, under thermal compressive strain loading, the overlapping slot pattern displayed a "birdcaging" deformation mode, with large slot openings, which significantly compromised the sand control functionality of the design (see Figure 3). The analysis showed that the overlapping slot pattern would not be suitable for use in most SAGD applications.

Drilling down to FEA results

Advancements in the industry's understanding of design factors for unconventional oil wells is ongoing—for instance, a future study is anticipated wherein the potential synergy effects of plastic material deformation and corrosion mechanisms on the long-term integrity of casing connections will be explored—and Xie looks to continue to advance C-FER's research capabilities and expertise with FEA-based projects. "With the help of Abaqus, we've been able to gain a far greater understanding of complex nonlinear and multi-physics processes in these unconventional recovery applications. The software has helped us fine-tune existing designs and predict the behavior of new ones for clients, long before they begin to drill and operate the wells. Overall, Abaqus has played a key role in improving the safety of oil and gas extraction while also providing significant business benefits from reduced downtime and failures."

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