COMPUTER-AIDED PROCESS ENGINEERING IN OIL AND GAS PRODUCTION

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Abstract

As oil and gas production moves to ever more challenging areas, increased use of technology becomes increasingly important. One technology that can contribute towards achieving safe and economic production from such areas is computer-aided process engineering. We outline the use of such technology in two (of many) instances: Managed pressure drilling (MPD) for deep-offshore applications and natural gas production from shales. A broader picture of the importance of computer-aided process engineering for energy is briefly touched upon.

Keywords

Oil and gas, Managed pressure drilling (MPD), shale gas, natural gas, unconventional resources

Introduction

It was less than a couple of years ago when the Macondo well accident in the Gulf of Mexico brought to the forefront the technological challenges and risks – for human life and the environment – faced by the oil and gas industry. At the core of the accident was undetected penetration of hydrocarbons from the rock formation into the well being drilled and subsequent loss of well control (BP, 2010). While the term *control* in the previous sentence has a different flavor from what is usually understood in the chemical industry (where process control typically refers to the use of automatic feedback for rejection of external disturbances and maintenance of process variables at their setpoints) well control also bears similarity to chemical process control – particularly of the advanced constrained control variety – in that the main objective of well control is to maintain the pressure in a well within well prescribed limits, for safety and performance reasons. To achieve this objective, well control technology has traditionally relied on a combination of well prescribed (no pun intended) work flows and the use of appropriate equipment. In that respect, well control bears similarities to aerospace control as well, where automation is fairly advanced with commensurate care for maintenance of situation awareness by human operators of automated systems (Endsley and Garland, 2000). In fact, in the perennial debate whether more or less automation is beneficial (in view of the risks and benefits associated with human involvement in controlling engineered systems) a crucial realization is that automation can be highly beneficial, as long as humans maintain situation awareness (Norman, 1990) and retain critical manual skills (Wiener and Curry, 1980), so that they can take appropriate action in situations for which automation is unprepared. Of the many lessons learned in the Macondo well accident, the lesson on the importance of human decisions as well as on the interaction between humans and machines cannot be overestimated.

Based on the preceding discussion it is fair to say that automatic control of hydrocarbon well drilling operations bears certain similarities to both chemical process and aerospace control, but it also has its own intricacies and challenges. While control of hydrocarbon well drilling can

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certainly draw from these disciplines, it certainly poses different enough problems to warrant research on such problems, a task for which chemical engineers have the background to make useful contributions. In fact, as we will outline below, concepts such as multi-level control and real-time optimization, well established in the chemical industry, can be directly transferred to the oil and gas industry.

A related story can be told about another development that has had a major impact on projections for our energy future, namely the very recent development of unconventional natural gas resources, particularly shale gas. While the term *unconventional*, by suggesting what such resources are *not*, provides little insight into what such resources are, the notion of *shale gas* refers to natural gas trapped in rock of very low porosity (2% or less) and permeability (0.1 to 0.0001 md or even less). Therefore, if a well were drilled into such rock, the gas would take an extremely long time to reach the well, and production would be so low that any economic extraction of such gas from the ground would be infeasible. What has made the recovery of shale gas economically attractive is the extensive use of two crucial technologies: directional drilling (Economides et al., 1988) and hydraulic fracturing (Economides and Nolte, 2000). Identified along with 3D-seismic imaging as the most crucial recent technologies for oil and gas exploration and production (Economides and Nikolaou, 2011), directional drilling and extensive hydraulic fracturing have resulted in dramatic increase of the *recoverable* natural gas reserves for the US, where shale gas production was pioneered in the Barnett Shale around 2005. The economic implications of this development should not be underestimated, as natural gas prices in North America have stayed significantly lower than elsewhere in the world and multi-billion dollar LNG regasification terminals built in the US just before the emergence of shale gas production suddenly became redundant in a market that no longer needed natural gas imports and could even afford exports. To appreciate the quantities of shale gas, suffice it to say that *proved* natural gas reserves in the US totaled about 175 Tcf in 1998; in 2009, after about 250 Tcf of production in the intervening years (around 23 Tcf/year on the average), US proved gas reserves *rose* to 285 Tcf.

It is now becoming evident that large quantities of recoverable shale gas can be expected in many other areas outside the US, e.g. China (Wang and Wang, 2011), Poland, the UK, and others, for currently estimated global reserves of about 16,000 Tcf, a figure that may change in the future. Developing a resource of such magnitude efficiently poses both engineering and environmental challenges (Moridis et al., 2011b; Sakmar, 2011).

In the rest of the paper we will dwell on some recent work on automated well control and on shale gas resource development. Our objective is to delineate major issues along with some specifics that help elucidate the bigger picture.

Drilling hydrocarbon wells

Drilling hydrocarbon wells is based on a simple principle: A rotating drill bit at the bottom of a drillstring (a long string of thread-joined pieces of pipe and tools suspended from a derrick) creates a hole into a rock formation. The rock cuttings are transferred from the bottom of the drilled hole to the surface by a circulating fluid (drilling “mud”), pumped from the surface to the bottom through the drill pipe and back to the surface through the annulus between the drill pipe and the well walls. The drill bit rotation is provided by drill pipe rotation or, for horizontal wells, by a bottomhole mud motor. The drilling mud serves multiple tasks, such as lubrication, protection of well walls from collapse or damage, and containment of hydrocarbons within the reservoir during drilling, to prevent a blow-out. As mentioned in the Introduction, the importance of failing to maintain wellbore pressure at the right level and to ensure that fluids from the reservoir do not enter the well became painfully familiar to the general public after the Macondo well accident and made *blow-out preventer* a household term.

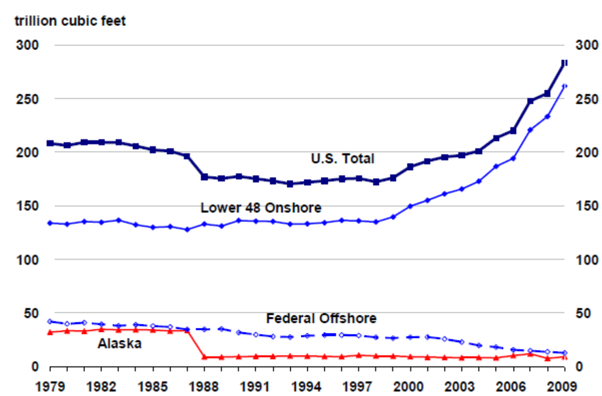

Figure 1. US wet natural gas proved reserves (Energy Information Administration, 2011).

Horizontal and multi-lateral well drilling started in the 1980s, and is now used routinely. Even though technically complex and costly, it offers distinct economic benefits, such as improved contact area with the reservoir (translated into improved hydrocarbon recovery – a particularly important factor for shale gas production), and a convenient- or single-entry point for exploitation of an entire reservoir (a crucial factor for offshore production, where the cost of a platform easily reaches billions of dollars).

Managed-pressure drilling (MPD)

Maintaining the health of a drilling system entails several concerns such as mechanical integrity and resiliency, vibration control (Spanos et al., 2003), weight-on-bit control (Nikolaou et al., 2005), drilling fluid flow and consistency, management of surface facilities (such as pumps, mixers, and storage tanks), and, crucially, pressure management in the borehole (Godhavn, Mar. 2009). This is a formidable challenge, given that a drillstring traverses several thousand feet into a rock formation, after going through several thousand feet of sea water for offshore applications. To enhance pressure control flexibility, efficiency, and safety, a number of drilling technologies, collectively known as managed pressure drilling (MPD) (Hannegan, 2007), have emerged as a powerful proposition for precise control of wellbore pressure. The primary goal of MPD is to keep wellbore pressure within constraints (Figure 2). To accomplish this, MPD typically employs a closed, pressurized mud circulation system, along with additional pumps, valves and chokes, in contrast to conventional systems where circulating mud is returned through an open line at atmospheric pressure. Because MPD treats the mud circulation system as a closed vessel, rather than as an open system, it offers higher flexibility and precision than traditional pressure adjustment based on mud weight and mud pump rate adjustments alone. However, this also generates operability challenges that have to be addressed before widespread acceptance of the technology (Rehm et al., 2008). These challenges emanate, in no small part, from (often non-trivial) interactions among different pieces of equipment and the need for coordinated control of their operation. Work flows that are well accepted in industry (and mostly based on human intervention) have to be adapted and further developed for use in MPD. More importantly, work flows based mostly on humans reach their limits when applied to MPD, given the limited capability of humans to handle reliably situations that involve several interacting variables simultaneously. Inability to handle such situations satisfactorily would result in significant economic loss through loss of productive time and could pose serious safety threats.

A solution is the use of enabling automation tools (Breyholtz et al., 2010a). Such tools can integrate MPD-related activities, allowing humans to concentrate on higher-level decisions, while leaving the reliable execution of lower-level decisions in an increasingly automated fashion. Separation of control tasks at multiple levels, separated mainly on time-scale, is crucial for such a critical automated system to work safely (Breyholtz et al., 2010b). It is also important to distinguish how varying degrees of automation affect situation awareness and workload on human operators during the execution of dynamic control tasks (Endsley and Kaber, 1999). In such situations there are generally four generic functions that can be performed either by human or computer: (1) monitoring: scanning displays to perceive system status; (2) generating: formulating options or strategies for achieving goals; (3) selecting: deciding on a particular option or strategy; and (4) implementing: carrying out the chosen option. Depending on the fraction of the preceding functions assigned to the human or computer, several degrees of automation can be established, as shown, for example, in Table 1 (Endsley and Kaber, 1999).

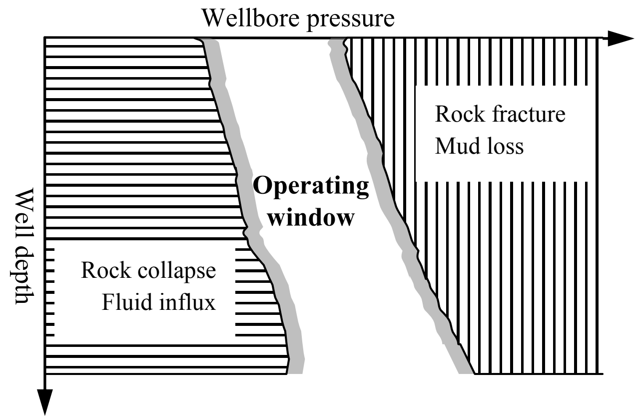

Figure 2. Operating window for wellbore pressure in the annulus between the drill pipe and well wall. If pressure violates its operating bounds, the rock may collapse, fluids from the reservoir may flow into the well (a "kick") possibly causing an accident, the rock may be fractured and/or drilling mud may be lost into the pores of the rock formation.

Table 1. Degrees of Automation

Degree of Automation	Function
Manual Control	Human performs all tasks (e.g. manual steering)
Computer Support	Computer aids human in decision making and implementation (e.g. cruise-control)
Consensual Automation	Computer implements control with human consent
Monitored Automation	Computer implements control unless vetoed by human (e.g. switch to manual mode)
Full Automation	No human interaction (e.g. "refrigerator mode")

Although automation has proven its reliability, safety, and ability to outperform humans in the chemical industry and its potential in other areas (e.g. traffic management (Godhavn et al., 1996) and aerospace control (Maciejowski and Jones, 2003)) MPD automation has been limited in the field, but its potential is growing (Godhavn, 2009; Thorogood et al., 2009; Godhavn et al., 2011). The driver is the need for improved safety and lower cost, particularly as oil and gas production moves to challenging offshore areas.

A glimpse of what can be achieved by MPD automation is given for the prototypical MPC system in Figure 3 (Breyholtz et al., 2010a). In this system, the objective is to maintain bottomhole pressure (BHP) close to a desired value and within safe bounds. Real-time measurements of BHP are available. At a certain point in time, the drillstring is first lifted, thus creating a void in the well that is filled with additional drilling fluid. After staying at this position for 10 minutes, the drillstring is then lowered to its previous position, now displacing drilling fluid. Following standard procedures, a human operator would concentrate on the position of the hook from which the drillstring is suspended, while keeping the flow rates of the main and subsea pumps constant. In contrast, a multivariable control system can clearly coordinate the flow rates of both pumps in such a way that pressure swings are reduced.

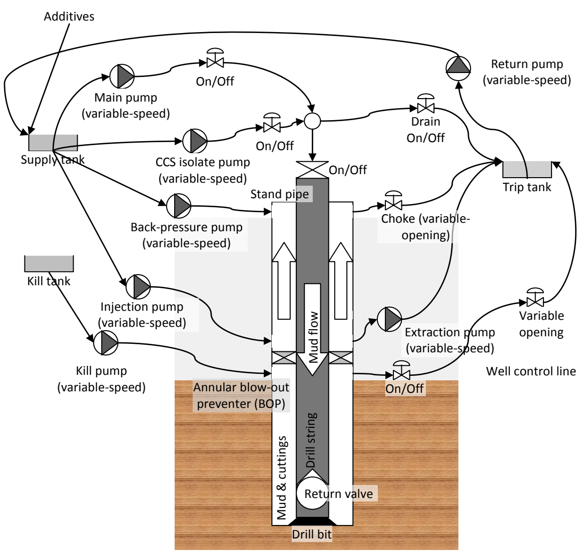

Figure 3. Generic MPD schematic. The similarity between this upstream system and typical downstream chemical plant or refinery units is obvious, and makes the case that process systems engineering and oil and gas production can both contribute to and benefit from each other's experiences.

Typical simulation results are shown in Figure 4 through Figure 6. It is not surprising that with the additional freedom to adjust pump flow rates BHP variation is reduced significantly. A few points should be emphasized here. The proposition to adjust pump flow rates, an innocent proposition for a control engineer, is all but certain to be met with scepticism by human operators. Therefore, to help increase the chance of acceptance of this new idea, the underlying hardware and related algorithms should be as robust as possible, even at the cost of inferior nominal performance. In that respect, the choice of MPC was based on simple engineering judgement: All that is needed here is a demonstrably sensible multivariable control approach that ensures good coordination of multiple variables while observing crucial constraints. In fact, involvement of and feedback from the intended final users during the development of related technology would be highly beneficial. At the same time, there should be firm commitment from management to support the installation, commissioning, operation, and further development of such new technology. Given the rich history of MPC, one could reasonably expect that many ideas from both practice and literature would be applicable, and that common themes suitable for fundamental investigation would emerge.

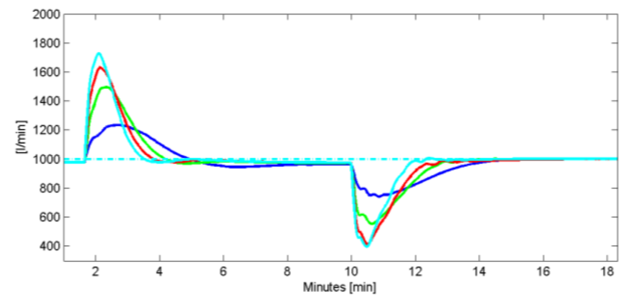

Figure 4. Flow rate from the main mud pump under the standard procedure (dashed line) and multivariable control for four different tunings (continuous lines)

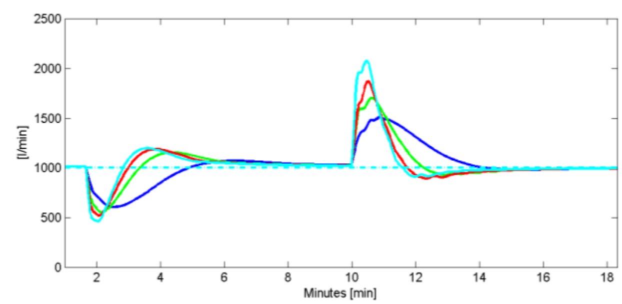

Figure 5. Flow rate from the subsea mud pump under the standard procedure (dashed line) and multivariable control for four different tunings (continuous lines)

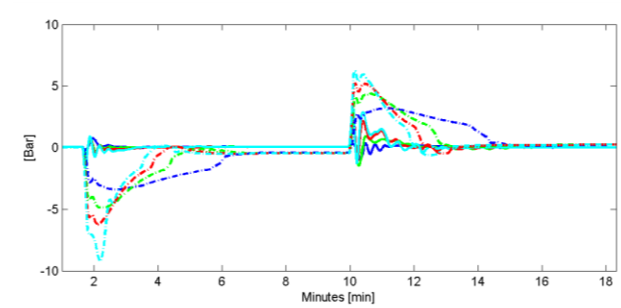

Figure 6. Variation in bottomhole pressure while moving the drillstring in and out of the borehole under the standard procedure (dashed line) and multivariable control for four different tunings (continuous lines)

Shale gas development

If drilling a hydrocarbon well is a conceptually utterly simple concept in principle, albeit extremely complicated in practice, increasing shale gas production through an extensively fractured horizontal increases conceptual difficulties only mildly, as indicated in Figure 7. Of course, the associated practical challenges increase significantly, to the extent that systematic design of shale gas field development systems stands to benefit from the availability of tools that aid engineers in a variety of decision making tasks. Such decisions have a significant effect on both production rate and recovery, as well as on economics.

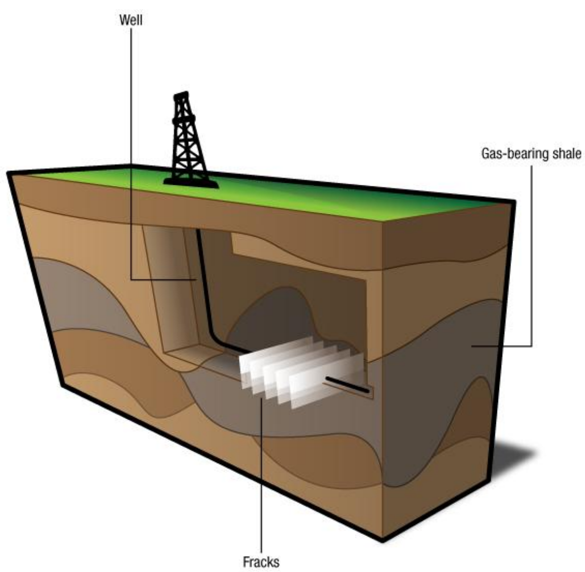

Figure 7. Extensively fractured horizontal well for development of a shale gas field

There are many questions that need to be answered when designing a fracture treatment, such as the following.

- How many fractures to place?
- What should be the fracture spacing?
- What kind of fracturing fluids must be used and in what quantity?
- What should be the time and rate of injection for each stage of well completion?

There have been many attempts in the recent years to address the above questions. A unified approach to fracture design that produces physically optimal designs given an amount of proppant has been proposed by Economides and co-workers (Economides et al., 2002). An approach that includes economics is summarized in Bhattacharya and Nikolaou (2011). The methodology proposed in the same reference relies on using best estimates of reservoir properties, design objectives, and design constraints to suggest an optimal design that maximizes net present value (NPV, Figure 8). This methodology is part of a broader effort (SeTES project) to build tools that can aid shale gas field development engineers who are continuously faced with the task of decision making using a variety of data from multiple sources that can easily make the burden overwhelming (Moridis et al., 2011b). SeTES is a software system that (a) can incorporate evolving databases involving a variety of types and amounts of relevant data (geological, geophysical, geomechanical, stimulation, petrophysical, reservoir, production) originating from unconventional gas reservoirs, i.e., tight sands, shales or coalbeds, (b) can continuously update its built-in pubic database and refine the underlying decision-making metrics and process, (c) can make recommendations about well location, orientation, stimulation, design and operation, (d) offers predictions of the performance of proposed wells (and quantitative estimates of the corresponding uncertainty), and (e) permits the analysis of data from installed wells for parameter estimation and continuous expansion of the public database.

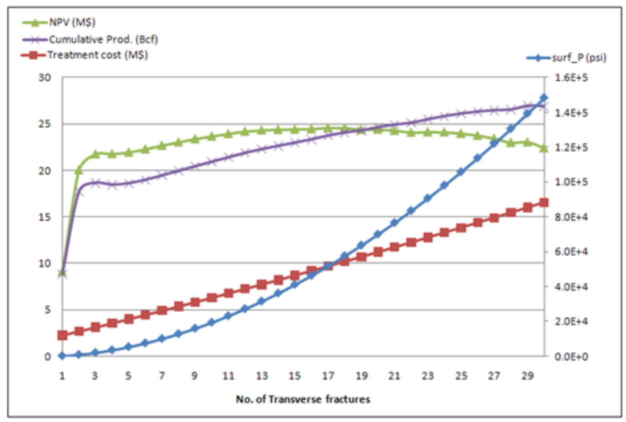

Figure 8. Trade-off between number of fractures and cumulative gas production vs. NPV for a shale gas well (Bhattacharya and Nikolaou, 2011). NPV is initially an increasing function of the number of fractures, until the point of diminishing returns is reached, after which additional gas production does not offset the additional cost of more fractures.

Closing thoughts

Although not the only or even the most important technology to impact the oil and gas industry, computer-aided process engineering can play an important role in future developments of the industry, as computer-based tools keep becoming increasingly powerful. We presented only a glimpse of recent developments in two areas: MPD control and shale gas development. In fact, the potential of computer and communications-based solutions has been widely recognized in the industry, as manifest by the recent proliferation of terms such as *intelligent fields* or similar to denote the extensive use of computers and communications for integrated, remote, and heavily computer-assisted work flows in drilling and production operations. In many respects, the development of such technologies is arguably only a matter of "just doing it", and adoption of such technologies in the field is constrained by other factors (Daneshy and Donnelly, 2004). In other respects, however, formidable challenges remain in practice, since implementation of the right technologies, suitably adapted and further developed for the field is all but trivial. Such challenges will keep emerging as oil and gas production is moving to places which only a short time ago would have been thought infeasible (e.g., deeper offshore, tar sands, gas and oil shales (unconventional resources (Stark et al., 2007)), the arctic (Aggarwal and 'Souza, 2011), natural gas hydrates (Moridis et al., 2011a), and others).

Of course, the bigger challenge is how far into the future the ultimate decline of oil and gas can be pushed through technology, while transitioning to alternative energy sources (Smalley, 2005). The time-scale of *ultimate* in the preceding sentence is highly uncertain. It is telling that projections (not to be confused with *predictions*) over the next 25 years portray an increase in the global use of all fossil fuels, with their percentage in the total energy make-up almost intact (Figure 9). It is actually ironic that coal, the cheapest fossil fuel but largest greenhouse gas (GHG) producer has increased the fastest since early 2000 (mainly because of China's frenetic economic growth). The non-interchangeability of different forms of energy should also not be missed. For example, US transportation currently runs almost entirely on oil (with corn-based ethanol recently making a small dent) whereas practically no oil is used for electricity generation. It is also interesting that switching from one fossil fuel (coal) to another (natural gas) could result in significant reduction of GHG emissions, albeit at a non-trivial cost. Finally the role of unforeseen rare events should not be underestimated either, as the Fukushima nuclear disaster in March 2011 exemplified. Interestingly, evolutionary nuclear technologies had been singled out by the NRC (National Research Council, 2009) as one of the two key CO2 emissions reduction technologies that should be immediately funded for large-scale development (the other being carbon capture and geological storage).

Regarding future developments, for which, we will stress, one can project but hardly predict, a systems approach will be crucial, in that energy systems – from generation to distribution to consumption – are highly integrated and optimizing or controlling one part does not result in global optimum. While the focus of this paper has been computer-aided process engineering for oil and gas, it can be convincingly argued that similar concepts are vital for the broader field of energy, and related contributions from chemical engineers would be both feasible and welcome.

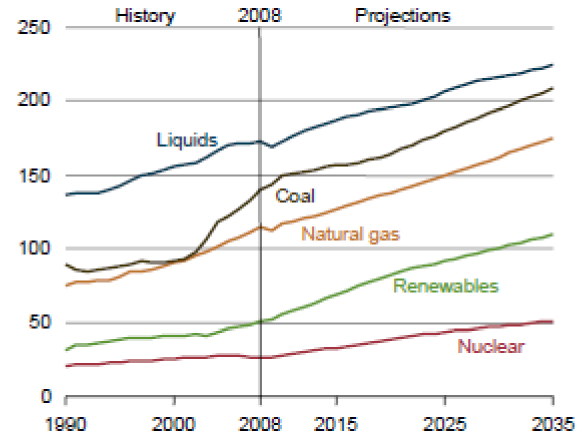

Figure 9. World energy consumption by fuel (Energy Information Administration, 2011)

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