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Online optimization for a plunger lift process in shale gas wells

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ABSTRACT

This paper presents a method for efficient optimization of a plunger lift process in shale gas wells. Plunger lift is a cyclic process consisting binary decision as well as continuous and discrete state variables. The time-series data comprising of surface measurements are converted into cycle-wise process-relevant performance outputs, while the binary manipulated variable is transformed into continuous threshold values. These transformed variables are used to develop a reduced order cycle-to-cycle model and corresponding receding horizon optimization problem that maximizes daily production while meeting operational constraints. The efficacy of the proposed algorithm is demonstrated on a simulated plunger lift process.

1. Introduction

Shale gas is categorized as an unconventional resource of natural gas. It accounts for nearly half of the natural gas production in the US and is growing worldwide as well (EIA, 2011). Shale gas is found trapped in low permeability shale rock formations, which occur about 2–4 km beneath earth's surface. Recent advances in hydraulic fracturing and horizontal drilling has made it economically viable to recover natural gas from shale reservoirs. While the initial production from a shale gas well is high, declining reservoir pressure causes the net production from a well to decline over time. Gas wells contain some amounts of liquids; either formation water, petroleum condensates or water left behind after fracking. With declining reservoir pressure, the liquids from the reservoir accumulate at the bottom of the well owing to insufficient pressure gradient between the reservoir and the well-head. This is called liquid loading, which causes a sharp decline in production rates (Lea and Nickens, 2004; Lee and Wattenbarger, 1996). Artificial lift refers to a range of methods that are used to remove the liquids from the well bottom to keep up the production (Lea and Nickens, 2004; Lea et al., 2008; Kaisare et al., 2013).

While liquid loading problems are common in both conventional and shale gas wells, there are some unique features of the latter (Knudsen and Foss, 2013; Lea et al., 2008). Shale gas fields are mostly inland and spread over a very large area, with multiple shale gas wells often drilled in proximity. Several wells share the surface production facilities, which can result in significant transient disturbances at the well-head. Furthermore, production from a shale gas well shows characteristic decline in gas production rate (Jenkins and Boyer, 2008; Knudsen and Foss, 2013). Finally, due to lower permeability, when a shale gas well is shut in for certain amount of time, the gas pressure in the well builds up than the liquid build-up, allowing the pressurized gas to deliquefy the well efficiently. Intermittent shut-in (Knudsen and Foss, 2013) and plunger lift (Lea, 1982; Lea et al., 2008) are two of the artificial lift techniques that exploit this property for efficient deliquefication of shale gas wells. Since they do not require expensive equipment, they are extensively used in shale gas wells. Specifically, plunger lift has gained wide-spread acceptance to optimize mid- and late-life production from inland natural gas wells.

Plunger Lift is a cyclically operated process that is used for deliquefication of conventional and unconventional natural gas wells (Lea et al., 2008; Gupta et al., 2017). A metal rod about one to three feet long, called *plunger*, is introduced in the shale gas well. A production valve is periodically manipulated to shut and open positions in a plunger lift cycle. The plunger falls to bottom of the well when the production valve is shut-in. After it reaches the bottom, liquids accumulate at the top of the plunger. When the production valve is opened and the gas starts flowing, the plunger rises to surface along with the accumulated liquid slug. In each plunger lift cycle, the system undergoes a sequence of (manipulated and autonomous) binary events – valve closing, plunger reaching well-bottom, valve opening, and plunger reaching the surface – that

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determine the overall process dynamics. Plunger lifted wells in shale gas field are usually instrumented with remote terminal unit (RTU), a microprocessor-based device which collects data, monitors performance and implements control actions.

Introduction of microprocessor-based well-head monitoring and control systems, in combination with the fact that it is inexpensive to install and operate (Morrow and Hearn, 2007) has resulted in plunger lift gaining popularity in the last two decades. Control of plunger lift is needed to ensure that the well is kept flowing and production rate is maintained (or maximized). An important operational objective is to ensure that the plunger arrives at the surface with the liquid slug in each plunger lift cycle. The plunger may fail to arrive at the surface if there is too much liquid buildup, insufficient gas buildup in the well or a large disturbance in production line pressure. Currently, an operator controls production from a well by setting shut-in and flowing times. This control is based on operators' experience or some heuristic rules (Gupta et al., 2014).

Although a modern plunger lift is easy to *operate*, it is challenging to *optimize and control* due to its hybrid dynamics and cyclic operation. Unlike typical periodic processes, plunger lift does not have a periodic trajectory or periodic disturbances. Similar to a batch process, the process dynamics are reset at the end of each cycle. However, unlike traditional batch processes, the system state is not reset at the end of a batch. Consequently, plunger lift may be viewed as hybrid system with continuous states and discrete events. The uncertain and transient flow conditions in reservoir, varying backpressure from production line, and the absence of downhole sensors (due to its high cost and reliability issues in extreme conditions) to measure conditions at the well-bottom pose additional challenges (Kaisare et al., 2013; Gupta et al., 2014). A hybrid state model (HSM) was developed in our previous work for simulating plunger lift process (Gupta et al., 2017).

The HSM-based model is computationally intensive for online optimization over multiple cycles. While use of hybrid systems framework for cyclic and batch processes is rather recent, Iterative Learning Control (ILC) and Repetitive Control (RC) have been successfully applied for control of batch and periodic systems, respectively, employing both first principles as well as identified models (Longman, 2000; Lee and Lee, 2007; Wang et al., 2009). However, models for control of cyclic systems involve "lifting", which results in large dimensional controller (Lee and Lee, 2007) and are time consuming to identify from data. Various control and optimization strategies for batch processes were reviewed by Bonvin et al. (2006), who organized them based on the nature of optimization objectives and control implementation. The objectives may be either run-time (e.g., tracking a trajectory) or run-end (e.g., productivity at the end of each run); likewise, the implementation may involve computing the manipulated inputs in real time or at the beginning of each batch (real-time or run-to-run implementations). Flores-Cerrillo and MacGregor (2003) presented within-batch as well as batch-to-batch control using latent variable MPC approach. Run-to-run or batch-to-batch optimization approach is suitable for systems with sparse (run-end) measurements with control actions injected at the start of each run using information from earlier runs (Lee et al., 2007; Bonvin et al., 2006). Kwon et al. (2015) presented run-to-run control of a batch process, whereas Busch et al. (2009) cast the problem of optimizing the batch time into a run-to-run (R2R) feedback control problem for a membrane filtration process.

The optimization objective in plunger lift is to manipulate switching of the binary production valve to maximize the net daily production rate, while maintaining plunger arrival speed as per specifications. Furthermore, the algorithm needs to be computationally efficient so that it may be implementable on a low-end RTU (remote terminal unit) as well. This paper presents a novel optimization approach for plunger-lift process that relies on predicting cycle-wise performance and optimizing it over multiple cycles in future. The binary manipulated input is converted into cycle-wise threshold values. A standard system identification based cycle-to-cycle model and receding horizon approach is modified to formulate the abovementioned optimization problem.

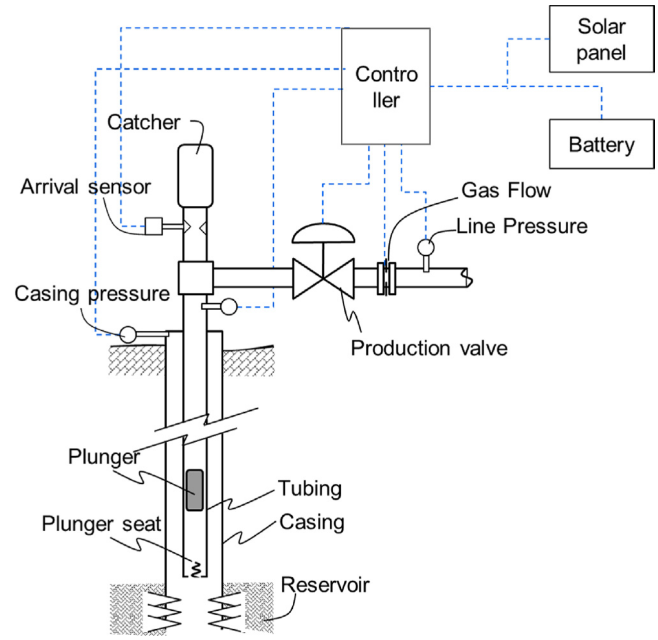

Fig. 1. Schematic of plunger lift operated shale gas well (adopted from Gupta et al., 2017).

The paper is organized as follows: Plunger lift process and the HSM model from our previous work (Gupta et al., 2017) is described in Section 2. The proposed optimization framework for the cyclic process is described in Section 3. Specifically, transformation of input/output time-series data into transformed input variables and cycle-wise outputs is presented, followed by a discussion of optimization formulation. Section 4 presents the simulation case study where proposed online optimization is implemented on a nonlinear plunger-lift (plant) model on a computer. Finally, Section 5 captures summary and conclusions of the work.

2. Plunger lift operation

2.1. Process description and model

2.1.1. Process description

Typically, a shale gas well is about 10,000 feet (3 km) deep with concentric tubes running down the depth as part of well construction. Fig. 1 depicts the pictorial view of a shale gas well operated by a plunger lift system. The outer shell, called the *casing*, provides structural strength to well while merging into the reservoir at the well bottom. The well bottom may have a horizontal section (not shown) to increase reservoir flows into the well. The reservoir fluids enter the well-bore through perforations in the casing. The inner tube, known as *tubing*, connects the well-head (surface) to the well-bottom (end of vertical section of well). Tubing at the well head is connected to the production flow *line* with a *production valve*. The production valve is a solenoid on/off valve, and opening or closing of this valve is the only manipulated variable that controls the plunger lift operation. A *plunger* is a cylindrical metal rod designed to snugly fit in the tubing, allowing a free vertical motion along the depth of the tubing while forming a piston-like seal with the inner walls of the tubing. The well-head is equipped with a spring assembly, known as *catcher*, at the surface end of the tubing to limit the