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Modeling of flow splitting for production optimization in offshore gas-lifted oil fields: Simulation validation and applications

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ABSTRACT

In modern offshore oil fields, wells can be equipped with routing valves to direct their production to multiple manifold headers, a strategy that is routinely adopted in practice either to provide resilience to equipment failure or to improve production. However, the existing models for production optimization do not account for splitting of flows and therefore require the wells to be connected to a single header. To this end, this work develops a nonlinear model of flow splitting that reproduces the complex behavior observed in multiphase-flow simulation. This model is further approximated with multidimensional piecewise-linear functions to a desired degree of accuracy with respect to simulated behavior. These piecewise-linear functions enable the development of a Mixed-Integer Linear Programming (MILP) formulation for production optimization, which decides between single and multiple routing of wells to headers. The effectiveness of this MILP formulation is assessed in a synthetic but representative gas-lifted oil field modeled in a standard simulator.

1. Introduction

The increasing demand for petroleum and the maturing of existing oil fields have compelled oil operators to invest in new technologies to optimize their production processes and cut operating costs. Further, the high costs of drilling and operating reservoirs put pressure on the operators to yield early returns on the investments, particularly so in the reservoirs of the Pre-Salt layer located off the coast of Brazil. To this end, the oil companies seek to optimize daily operating plans which consist of gas-lift injection rates, production choke openings, well-manifold routings, and pressures, among others. Such initiatives are aligned with the concept of Smart Fields (Yeten et al., 2004; Camponogara et al., 2010) which aim to drive production and economic gains by effectively integrating subsea equipment, control and information systems, and optimization software.

Because Smart Fields is an evolving technology, field engineers still rely on sensitivity analysis using simulation software and heuristics to decide upon the daily operational plans and respond to unanticipated events, such as compressor failure and pipeline clogging. However, this strategy can be rather time-consuming and does not necessarily ensure a mode of operation that maximizes the daily production.

An alternative that is gaining acceptance in the industry is model-based optimization, which can be viewed as the integration of mathematical models with algorithms into effective optimization tools. Such models should be routinely updated with field data to reflect the prevailing system conditions. For steady surface conditions and satellite wells, models and algorithms have appeared in the technical literature (Buitrago et al., 1996; Fang and Lo, 1996; Alarcón et al., 2002; Camponogara and de Conto, 2009; Misener et al., 2009; Codas and Camponogara, 2012). On the other hand, more complex models have been proposed to account for varying operating conditions, which are typical of production systems with subsea completion (Litvak and Darlow, 1995; Kosmidis et al., 2004, 2005; Gunnerud and Foss, 2010; Codas et al., 2012; Silva et al., 2012). For instance, the production of wells can be gathered in a subsea manifold before flowing to an offshore oil platform—therefore, the well-head pressure and pressure drop in the well jumper will depend on the manifold to which the well is connected.

In modern offshore oil fields, wells are often equipped with routing valves to direct their production to multiple manifold headers, a strategy that is routinely adopted in practice either to provide resilience to equipment failure or to adjust the well-manifold routings to improve production. Despite flow splitting being a common practice in industrial settings, to the best of our knowledge it is not accounted for by existing mathematical models in the optimization literature, whose works usually impose a single routing from wells to manifolds. Incidentally, flow

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splitting induced by routing well production to multiple manifolds is a common practice in the Urucu field, a reservoir located in the heart of the Amazon, which is not addressed by the existing models (Codas et al., 2012). To this end, this paper advances previous works by proposing a model that decides upon the splitting of flows in pipelines.

The paper is organized as follows. Section 2 proposes a mathematical model for flow splitting according to the observed behavior of a commercial multiphase-flow simulator. Section 3 approximates this model with piecewise-linear functions which are then validated against the simulator. Section 4 discusses the modeling of a synthetic, but representative field, and proposes a methodology to obtain sufficiently accurate Piecewise-Linear (PWL) models for well-production and pressure drops. Section 5 evaluates the performance of the PWL formulation and analyzes the impact of flow splitting. The concluding remarks are presented in Section 6.

2. Flow splitting modeling and validation for production optimization

A typical offshore production system is composed of subsea wells, manifolds gathering production from wells, and surface facilities. Production wells are equipped with choke valves that control well-head pressure and production, which can benefit from gas-lift to increase the flow rate. After being gathered by a manifold, the well production is directed to a surface separator which splits the production stream into three-phase flows, namely, oil which is transferred by shuttle tankers to an onshore terminal, gas which is compressed and exported in subsea pipelines, and water which is processed before discharge.

Fig. 1 illustrates a subsea production system consisting of a single well and three manifolds gathering production. The pressures and flow rates depicted in the figure correspond to the well-head pressure (p^n_{wh}), the pressure downstream the choke (p^n_{ds}), the manifold pressure (p^m), the well production ($\mathbf{q}^n$), the flow rates in the jumpers ($\mathbf{q}^{n,m}$), and the lift-gas rate (q^n_{inj}).

In such fields, operators usually decide upon the routing of production from wells to manifolds, which are implemented by opening or closing the routing valves. To the best of our knowledge, previous works found in the technical literature enforce the policy of routing wells to a single manifold (Gunnerud and Foss, 2010; Codas et al., 2012), despite multiple routing being routinely implemented in real-world oil fields.

In what follows, a mathematical nonlinear model for flow splitting is developed in the context of a single well and multiple manifolds. This model can be used to represent flow splitting of wells in complex production networks encompassing several wells and multiple manifolds.

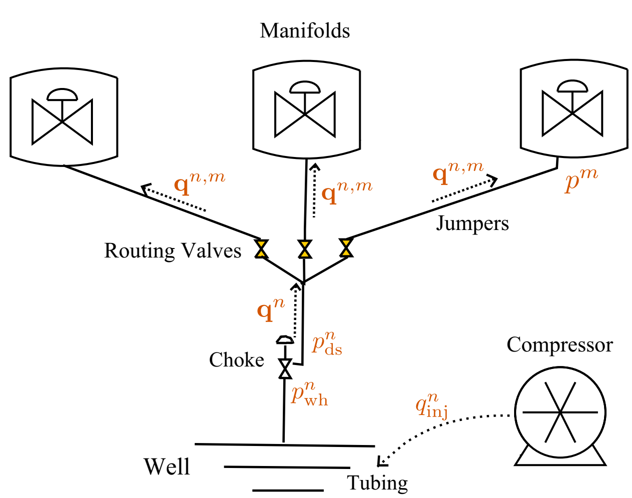

Fig. 1. Flow splitting illustration.

2.1. Nonlinear model

Consider a particular gas-lifted well n of a set $\mathcal{N} = \{1, \dots, N\}$. Suppose that well n can send its production stream to a subset $\mathcal{M}_n$ of the manifolds, with $\mathcal{M}_n \subseteq \mathcal{M} = \{1, \dots, M\}$. The oil, gas, and water produced by well n can be characterized by the following equations:

$$\begin{cases} q^n_{\text{oil}} = \widehat{q}^n_{\text{liq}}(p^n_{\text{wh}}, q^n_{\text{inj}}) \cdot (1 - \text{WCUT}^n) \\ q^n_{\text{gas}} = \widehat{q}^n_{\text{liq}}(p^n_{\text{wh}}, q^n_{\text{inj}}) \cdot \text{GLR}^n + q^n_{\text{inj}} \\ q^n_{\text{water}} = \widehat{q}^n_{\text{liq}}(p^n_{\text{wh}}, q^n_{\text{inj}}) \cdot \text{WCUT}^n \end{cases} \tag{1}$$

with $\widehat{q}_{\text{liq}}$ being the liquid production as a function of the well-head pressure p^n_{wh} and the rate of the lift-gas injection q^n_{inj}. For the purpose of steady-state production optimization, the gas–liquid ratio (GLR) and the water cut (WCUT) are assumed known and constant over the horizon of production planning.

The difference between the well-head pressure and the pressure downstream the choke, p^n_{ds}, corresponds to the pressure loss due to friction which is related to a particular choke opening. Flows in the jumper connecting well n to manifold m are given by functions as follows:

$$\mathbf{q}^n_{\text{sp}} = \widehat{\mathbf{q}}^n_{\text{sp}}(\mathbf{q}^n, p^n_{\text{ds}}, \mathbf{p}^n_{\text{man}}), \tag{2a}$$

$$\mathbf{q}^n = \sum_{m \in \mathcal{M}_n} \mathbf{q}^{n,m}, \tag{2b}$$

$$\mathbf{q}^m = \sum_{n \in \mathcal{N}_m} \mathbf{q}^{n,m}, \tag{2c}$$

$$p^n_{\text{wh}} \geq p^n_{\text{ds}}, \tag{2d}$$

$$p^n_{\text{ds}} = \widehat{\Delta p}^{n,m}_{\text{jp}}(q^{n,m}_{\text{liq}}, \text{GOR}^{n,m}) + p^m, \quad m \in \mathcal{M}_n \tag{2e}$$

$$\text{GOR}^{n,m} \cdot (1 - \text{WCUT}^n) = \text{GLR}^n + \left(\frac{q^n_{\text{inj}}}{q^n_{\text{oil}} + q^n_{\text{water}}} \right), \quad \forall m \in \mathcal{M}_n \tag{2f}$$

where

1. $\mathbf{q}^n = (q^n_{\text{oil}}, q^n_{\text{gas}}, q^n_{\text{water}})$ is a vector with the three-phase flow produced by well n,
2. $\mathbf{q}^n_{\text{sp}} = ((q^{n,m}_{\text{oil}}, q^{n,m}_{\text{gas}}, q^{n,m}_{\text{water}}) : m \in \mathcal{M}_n)$ is a vector with the rate of all fluid phases flowing in the jumpers,
3. $\mathbf{p}^n_{\text{man}} = (p^m : m \in \mathcal{M}_n)$ is a vector with the pressure of the manifolds receiving the production stream from well n.

The three-phase flows in the jumpers are given by the function $\widehat{\mathbf{q}}^n_{\text{sp}}(\mathbf{q}^n, p^n_{\text{ds}}, \mathbf{p}^n_{\text{man}})$ which depends on the total flow rate $\mathbf{q}^n$ of well n, the pressure downstream the choke (p^n_{ds}), and the pressures at the manifolds to which the well is connected ($\mathbf{p}^n_{\text{man}}$). A multiphase-flow simulator iteratively calculates the flow for each jumper based on the pressure differences downstream the choke to the manifold, keeping the same gas–liquid ratio of the well in accordance with Eq. (2f). Notice that the left-hand and the right-hand side of Eq. (2f) define a factor that, when multiplied by a flow of liquid, produces the respective flow of gas. This factor is the gas–liquid ratio (GLR) for the jumper on the left-hand side and for the well on the right-hand side. The pressure drops in the jumpers are calculated by the function $\widehat{\Delta p}^{n,m}_{\text{jp}}$, being induced by the flows.

Typically, the functions $\widehat{\mathbf{q}}^n_{\text{sp}}$ and $\widehat{\Delta p}^{n,m}_{\text{jp}}$ are not known explicitly but rather implemented by simulation software, which iteratively converges to a solution of the system of equations (2) that