Real-Time Pipeline Monitoring

Online multiphase flow simulation technology allows operators to perform flow assurance on a daily basis.

Over the years, the operation of multiphase subsea production systems has presented a variety of challenges to upstream operators. Flow assurance is a term generally used to refer to all issues important to maintaining the flow of oil and gas from reservoir to reception facilities. Flow assurance starts at the design phase, using multiphase flow simulation tools that provide design guidelines such as appropriate pipeline sizing and insulation, and also help set operating philosophies such as startup procedures, blow-down procedures, and pigging frequency. Some of the most talked-about issues in flow assurance are slugging, hydrate plugs, wax deposition and asphaltene precipitation.

Today, real-time, online, transient multiphase flow simulation technology exists that allows the operator to perform flow assurance on a day-to-day basis. The goal here is to introduce the high-level concepts that make this technology robust enough to be applied in an operational environment, and also be used as advisory systems to make operational decisions. Thus, this discussion seeks to: (a) touch upon some technical aspects of the design of online multiphase simulators, and (b) illustrate that not only are these simulators necessary, but they can simplify complex operational decisions to the push of a button.

This case study is presented in two parts. The first part shows that while design tools in and of themselves may be accurate, the model is only as good as the data that is fed in. These authors have seen instances where faulty design data resulted in studies under-predicting liquid holdups for nominal flowrate cases by as much as 33%.

Following this, we believe it is useful to discuss the fundamental modeling concepts in multiphase flow simulation, including a head-to-head comparison of multiphase flow simulation design tools versus online simulation tools. Finally, some specific applications of online multiphase flow simulation are discussed, including pipeline monitoring, inferential flow metering and leak detection.

Case study – Part I
Field performance of a specific gas-condensate pipeline differed vastly from design data, necessitating changes to the pipeline model assumptions in order to replicate observed field behavior. The online model was tuned to match the steady-state total liquid holdup predicted by the design tool for the 58-mi, 36-in. subsea three-phase pipeline before site installation (Figure 1). After the online model was installed and tuned to field data, it was observed that at typical production rates of around 800 MScfd, the design tool had under-predicted the holdup by as much as 33%.

Sources of error
The point of the example is not to show that the design tool is flawed. It is rather
to bring out the fact that assumptions made at design time may not always hold true in reality. The impact of this is that operational guidelines developed as part of design may not necessarily be “safe” for operations.

One source of error was the bathymetry data. A smoothed version, instead of the actual bathymetry, was entered into the design simulations. This changed the angle-class distribution, which has a significant impact on the holdup. Further, Table 1 summarizes the fluid property differences between the tuned model and the design case.

**Simulation technology**

Multiphase pipeline simulation has made significant progress over the last two decades, and is now able to handle complex converging and diverging networks, and incorporate advanced thermodynamic calculations to facilitate modeling the phenomena observed in field operations. However, in a design simulation system, all the inputs to the model are idealized and perfect, and in an online system the inputs to the model are inaccurate and noisy, or sometimes even unavailable. Here, it is useful to briefly explain some of the fundamental modeling concepts, and discuss how online systems differ from a design tool, and the forces driving these differences.

**Fundamental concepts**

Transient multiphase pipeline simulation involves combining numerical models of different physical phenomena. These can include hydrostatics, heat transfer, thermodynamic equilibrium of hydrocarbon mixtures, and multiphase non-Newtonian fluid dynamics, in increasing order of complexity.

### Heat transfer

Fluids are produced at high temperatures and lose heat to the colder surrounding environment primarily via radial flux through the pipe wall. Axial temperature gradients along the length of the pipe (and associated heat transfers) can be neglected.

A rigorous approach to modeling the heat transfer between the fluid, pipe wall, soil and water would be to use a finite-element approach to model the cross section of a pipeline profile as a 2D grid. However, a simpler approach is usually adopted where it is reduced to a one-dimensional model depending only on the radial axis.

### Thermodynamic calculations

Accurate fluid property estimation is critical to multiphase flow simulation. Firoozabadi provides a comparison of various cubic equations of state (EOS) and their performance as applied to typical reservoir fluids.

### Multiphase flow model

One of the primary difficulties in modeling multiphase flows is the existence of multiple flow regimes, which is a function of gas-liquid ratio, superficial velocities and pressure. The simplest of these flow regimes is stratified flow, which is typical in a gas-condensate system, where gas flows along the top of the pipeline, pulling the liquid at the bottom along at a lower velocity. A mechanistic model can be

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**Table 1. Fluid properties at 85 bar and 20°C.**

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Gas</th>
<th>Liquid</th>
<th>Gas</th>
<th>Water</th>
<th>HC Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuned</td>
<td>0.2137</td>
<td>0.7863</td>
<td>68.5</td>
<td>18.9</td>
<td>1.06</td>
</tr>
<tr>
<td>Design</td>
<td>0.1760</td>
<td>0.8240</td>
<td>67.6</td>
<td>19.1</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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**Table 2. Comparison of multiphase pipeline simulator goals as design and online tools.**

<table>
<thead>
<tr>
<th>Design tool</th>
<th>Online model</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary conditions</td>
<td>Inlet flowrate and outlet pressure are used for model predictions. Use as much information as is available to model predictions of other measured quantities, such as outlet flow rates, are closer.</td>
<td></td>
</tr>
<tr>
<td>Assumed fluid composition at inlet</td>
<td>Estimated composition that results in the right gas-liquid ratio observed at the receiving facility. Fluid composition at the inlet is usually sampled very infrequently.</td>
<td></td>
</tr>
<tr>
<td>Assumed inlet temperature</td>
<td>Measured inlet temperature. If multiple wellhead streams blend, use enthalpy balance to determine mixture temperature. If mixture temperature is measured, use it. VLE is a very strong function of temperature. In predominantly liquid systems, small differences in temperature could mean big differences in fluid properties such as density and heat capacity.</td>
<td></td>
</tr>
<tr>
<td>Tuning</td>
<td>Design tool is not customized for each facility. Therefore, out of the box, these tools need to predict pipeline conditions as accurately as possible. Online pipeline simulators need to be tunable to field measurements. It is important to match observed field behavior over all operating conditions within instrument accuracies. Online simulators are not used to make design decisions. They are advisory systems for making operational decisions. If the simulator has been predicting observed field behavior, say, gas and liquid flow rates within 5% over the last few days, operations can have the confidence that it will have the same accuracy looking into the future.</td>
<td></td>
</tr>
<tr>
<td>Instrument error handling</td>
<td>No need for this functionality. Very important to maintain integrity of model prediction. In more advanced applications such as model-based leak detection, need to automatically compensate for instrument drift. Closed-loop control applications need even more advanced data reconciliation algorithms.</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>Can afford to be slower and more rigorous. Needs to have varying degrees of rigor. Look-ahead forecasts need to run rapidly to be usable planning or advisory tools.</td>
<td></td>
</tr>
</tbody>
</table>
developed for simulating stratified flow based on governing transport phenomena of mass, momentum and energy transfer. The equations can be solved by “discretizing” the pipeline, and using a numerical solution approach such as finite difference method.

**Online model**
The online model comprises several aspects, discussed below.

**Heat transfer**
Water (ambient) temperature, the most critical piece of information required to accurately model heat transfer, is usually not available as a real-time instrumented measurement. In places with wide variability in seasonal temperatures, this is an issue that needs attention. In deep water, a single ambient water temperature may be assumed.

**Thermodynamics**
In design studies, full-stream compositions are assumed. In online systems, compositions are rarely available in real-time. In fact, one would be lucky to get well samples more than once a year. The tuning purpose is to match the vapor-liquid ratio arriving at the receiving facility. This same approach was used in characterizing the produced fluid in the case study. Online models should be capable of using a gas composition, and a condensate and water loading at the inlet. If gas compositions from different sources are available, it should blend them dynamically where the different fluids mix in the network to predict VLE and other fluid properties.

**Other boundary conditions**
Inlet flow rates may be available in different forms, including multiphase meters, wet gas orifice plate meters, venturi meters with correlations to predict phase flow rates, individual phase flow rates downstream of a production separator where the fluids are blended back in, gas phase measurement on individual wells, but commingled liquid measurement, etc. The model should be flexible enough to handle any of these (and more) combinations so that much of the instrumented data can be used. Advanced filtering logic needs to be available to handle instrument failures, redundant instrumentation, and communication losses.

**Other considerations**
Even with the perfectly instrumented field, a transient multiphase pipeline model is just that - a model. More to the point, the online model is one built by combining some simplified models (for speed) of physical phenomena with some empirical models of phenomena for which either no first-principle models exist, or are unsolvable. Therefore, each of these physical and empirical models needs to have adjustable parameters that allow the user to match model predictions with corresponding observable quantities. In some cases, this occurs naturally; for example, the pressure drop in a pipe segment can be directly adjusted by changing the pipe friction coefficient. Other models do not lend themselves to tuning easily; however, tuning is an absolute requirement for the online model to be usable. Table 2 presents a comparison of multiphase pipeline simulator goals as design and online tools.

**Case Study – Part II**
In the case presented above, the operations team needed a utility (a software solution) from which its pigging campaigns could be planned. The pigging planner utility is built on top of an existing online transient multiphase pipeline model. The model also includes some dynamics of the slug catcher, including its level indications.

**Pigging utility**
A pigging utility was developed that provides a way to plan the pigging campaign to ensure that slug catchers will not be flooded during the process. The online model was then tuned to field data collected from various pigging campaigns.

Planning of the pigging campaign begins with the current estimated pipeline state from the online model (Figure 2). Alternatively, several “condition” files can be generated that are states to which the pipeline will be brought before start of the pigging campaign. Any of these can be used as the starting point for campaign planning.

**Usability requirements**
One of the more important requirements of an online model is that it be wrapped in a nice operator-friendly interface.
Although the end users of a design tool are engineers, the end users of an operational tool should be the operators. Some of the salient features of the pigging utility that highlight this importance are as follows:

- Avoiding usage of modeling terms such as boundary conditions, outlet pressure (instead use SC pressure).
- Outputting post-processed quantities that are relevant to operations. For example, indicated level of condensate is not the actual condensate level in the slug catcher because water swept out during pigging usually exceeds the limits of the water level indicator. Thus, the condensate level is condensate plus water.
- The operator is able to specify condensate and water loading instead of a full wellhead stream composition, which is unavailable.
- Ability to use different units sets. Although, in this application, the units are standard oilfield units, in some parts of the world, SI or some other units may be used. Users should always be able to input model parameters in units with which they are familiar.

Applications

Real-time pipeline monitoring using online simulators is the first step in leveraging the technology. Some of the applications include:

- Provide real-time estimates of liquid holdup, pressure, temperature and flow rate along the length of the pipeline.
- Track pigs and pig-generated liquid slug volumes as they move.
- Predict closeness to hydrate formation, wax deposition, and asphaltene precipitation along the line.

These applications also have look-ahead capabilities, i.e., to automatically forecast the state of the facility some hours into the future to help prevent bad events. For example, in a deepwater system, a cool-down look-ahead module can take the current state of the pipeline and estimate the time available before hydrates will form, if the production were to shut down immediately.

Leak detection of subsea multiphase flow lines, especially in deep water, is feasible only using model-based methods. Studies have shown that model-based leak detection which combine statistical analysis of differences between model-predicted and measured quantities (such as inlet pressure) are the only reliable method for detecting leaks in transient multiphase production systems.

Inferential metering is another application of online multiphase flow simulation that could save millions of dollars in capital and operational expenditures. Inferential metering is software-based multiphase flow metering that utilizes pressure, temperature and choke measurements typically available down-hole and on the production tree. This application completely replaces physical multiphase flow meters (MPPMs). Using inferential metering, individual well flow rates are available in real-time, without the installation of costly MPPMs.