Statistics & Control, Inc.

White Paper

OptiRamp® Real-Time Multiphase Flow Simulation System

Accurately Simulate Multiphase Flow in Pipelines

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Introduction

Pipelines in oil and gas production systems normally transport multiphase mixtures of oil, water, and gas. Simulating complex multiphase flow processes is an important aspect of efficient oil field operation as safety and optimization rely on a detailed understanding of multiphase flow behavior.

The *OptiRamp*® multiphase flow model uses conservation laws and well-established empirical formulas to simulate changes in the mass flow rate and thermodynamic properties (pressure, temperature, etc.) of single- or multi-phase fluids transported across industrial-scale pipelines. A diverse set of equations of state are employed to allow the *OptiRamp* multiphase flow model to simulate a wide variety of materials and to ensure that it can handle the difficulties that arise from fluid compression and phase transitions. When modeling the transportation of water/steam mixtures (that do not include contributions from oils or other gases), the *OptiRamp* Simulator also determines changes to the steam quality (i.e., the composition of the water/steam mixture).

Predictions made by the multiphase flow model are then used as input data by the other software modules included in the *OptiRamp* suites to perform a number services, including

- Optimize the operating mode of the pipeline in a manner that will maximize production, minimize operation cost, or increase profit
- Track the condition of equipment operating the pipeline and determine the optimal time to perform necessary equipment maintenance
- Train operators and maintenance personnel

Scientific Foundation

Multiphase flow processes involve a combination of materials with different properties and that often exhibit relative motion among the phases. The multiphase flow model is designed to predict the fluid properties, mass flow rate $\dot{m}$, pressure P, and temperature T of a fluid at different distances along the pipeline x and at different moments in time t. In order to make these

predictions, the initial mass flow rate and composition (relative amounts of oil, water, and gas) of the fluid must be specified. Values of the key physical properties (density, viscosity, etc.) of the fluid must also be identified either by using empirical formulas to calculate those values or by specifying them as input parameters.

Once the necessary input parameters have been specified, several mathematical algorithms work in consort to determine the changes to $\dot{m}$, P, and T. Specific algorithms used at a given point of the pipeline are chosen to account for the dominant forces that affect the fluid properties at that point.

Conservation Laws

The basis of the multiphase fluid simulation is the formulation of a set of conservation equations. For the majority of the points along the pipeline, the motion of the fluid is governed by three conservation laws: mass, momentum, and energy. The conservation of mass dictates that matter cannot be created or destroyed. For fluid flow through a pipe, this law can be expressed according to equation (1):

$$\frac{\partial(A\rho)}{\partial t}+\frac{\partial(vA\rho)}{\partial x}=0, \tag{1}$$

where ρ is the density of the fluid, v is the superficial velocity of the fluid, and A is the cross-sectional area of the pipe. When pipe thermal expansion is ignored, equation (1) indicates that the change in the mass flow rate along the direction of the pipe can be determined from the rate of density change, $\frac{\partial\dot{m}}{\partial x}=-A\frac{\partial\rho}{\partial t}$.

The conservation of momentum determines the change that occurs to the momentum of the fluid due to forces directed towards or against the direction of its flow. When a fluid flows through a pipe, three forces affect its movement: gravitational, F_{grav}; frictional, F_{Fric}; and fluid pressure gradient, $F_{\nabla P}$. Based on the conservation of momentum, the equation (2) determines the combined influence that those three forces have on the fluid's momentum.

$$\rho\frac{\partial v}{\partial t}+\rho v\frac{\partial v}{\partial x}-F_{grav}-F_{Fric}-F_{\nabla P}=0 \tag{2}$$

Mathematically, the gravitational and pressure gradient forces can be described by the following equations, $F_{grav}=-\rho g\sin\theta$ and $F_{\nabla P}=-\frac{\partial P}{\partial x}$, where g indicates the acceleration due to gravity and θ denotes the pipe's angle of elevation. Unlike gravity and pressure, the nature of friction is not well defined. For laminar (i.e., streamline) flow, the frictional force can be rigorously determined from the expression $F_{Fric}=-\frac{64}{N_{Re}}\frac{\rho v^2}{2D}$, where D specifies the diameter of the pipe, $N_{Re}=v\rho D/\mu$ denotes the fluid's Reynold number, and μ represents the fluid's viscosity. For transitional and turbulent flow, an empirically determined friction factor, f, is used in place of

$\frac{64}{N_{Re}}$, $F_{Fric} = -\frac{f\rho v^2}{2D}$. The value of the friction factor is implicitly determined from the Colebrook equation, $\sqrt{\frac{1}{f}} = -2.0\log_{10}\left(\frac{1}{3.7}\frac{\varepsilon}{D} + \frac{2.51}{N_{Re}\sqrt{f}}\right)$, and is a function of the Reynold number of the fluid and the diameter and roughness (ε) of the pipe.

The final conservation law that must be obeyed is the conservation of energy. The conservation of energy states that the total energy of the fluid, pipe, and surrounding environment will remain constant. This means that the rate that energy changes within a small segment of the pipe is equal to the change in energy due to fluid movement through the pipe minus the sum of the amount of energy used to compress the fluid and the amount of heat dissipated through the wall of the pipe into the surrounding environment. Mathematically, that relationship is expressed by equation (3):

$$\frac{\partial E_{Fluid}}{\partial t} + v\frac{\partial E_{Fluid}}{\partial x} + \frac{P}{\rho A}\frac{\partial (vA)}{\partial x} + \frac{v}{\rho}\frac{\partial P}{\partial x} + \frac{4K(T - T_{Amb})}{\rho D} = 0\,, \tag{3}$$

where $E_{Fluid} = \frac{1}{2}v^2 + gx\sin\theta + U$ denotes the total energy of the fluid per unit mass, U is the specific internal energy of the fluid, K specifies the insulation (or heat-transfer) factor of the pipe and its surroundings, and T_{Amb} specifies the ambient temperature of the environment surrounding the pipe. Equation 3 can be further simplified by expressing the time (and distance) derivatives of the specific internal energy in terms of the fluid's specific heat capacity, the fluid's elasticity, and the time (distance) derivatives of the temperature and pressure.

Based on equations 1 through 3, finite difference algorithms were developed for the *OptiRamp* multiphase flow model that separate time into small time steps and separate the length of each pipe into small pipe segments. The current values for the pressure, temperature, and mass flow rate at a given time and at the start of each pipe segment are then used in discrete forms of equations 1 through 3 to determine the values of P, T, and $\dot{m}$ for each pipe segment at the start of the next time step.

Empirical Formulas and Machine Characteristic Curves

The conservation laws are used to describe the gradual changes that occur to $\dot{m}$, P, and T as a fluid flows through the pipeline. An accurate application of those laws is essential for the development of a reliable flow model. However, the simplified versions of those laws shown in equations 1 through 3 are not capable of modeling the points of the pipeline where the fluid encounters sharp bends in the pipe or sudden changes in the diameter, roughness, and other properties of the pipe (i.e., the fittings that connect each pair of pipes). On their own, the conservation laws are also not capable of describing the changes produced in the fluid by compressors, pumps, and other industrial equipment. Instead, well-established empirical formulas and experimentally determined mechanical characteristic curves are used to model those areas of the pipeline and to determine the efficiency and power requirement of each piece of industrial equipment connected to the pipeline. Empirical formulas are also used to predict the properties of the fluid at its source (i.e., at the oil production wells, steam generators, etc.).

Modeling the Merging or Splitting of a Fluid at the T-junctions

When T-junctions that merge two fluid streams into one are encountered, a combination of ideal solution mixing rules and empirically determined mixing formulas are employed to compute the composition and chemical properties of the combined fluid. At T-junctions that distribute the fluid between two pipes, steady-state treatments of the mass and energy conservation laws are used to identify the mass flow rates of each channel.

Modeling the Flow of Multiphase Fluids

When designing a multiphase flow model, it is important to carefully consider each algorithm used and determine whether or not it depends on the fluid nature. For instance, the conservation laws are universal and describe the motion of any type of fluid, including multiphase fluids. Only formulas used to evaluate the molecular properties and the friction factor need to be modified. Likewise, the empirical parameters needed to calculate the sudden changes to $\dot{m}$, P, and T at each pipe fitting do not depend on the fluid properties, meaning the formulas that depend on those parameters do not need to be changed when dealing with multiphase fluids.

Physical and Chemical Properties

Accurate values for the extensive properties ($\dot{m}$, v, etc.) of a multiphase fluid can be approximated as the sum of the properties computed for the liquid and gas phases of the fluid, i.e,. $\dot{m} = \dot{m}_l + \dot{m}_g$. In contrast, the intensive properties (ρ, c_v, etc.) of a multiphase fluid should be determined by averaging the values of the corresponding gas and liquid phase properties, i.e., $\rho = \varpi_l \rho_l + (1 - \varpi_l)\rho_g$, where ϖ_l denotes the liquid holdup of the segment of the pipeline that is being evaluated.

Formally, the liquid holdup for a given section of the pipeline is defined as the ratio of the volume of liquid that is contained in that section of the pipeline to the volume of that section of the pipeline, as shown in equation (4)

$$\varpi_l = \frac{\text{volume of liquid in a section of the pipeline}}{\text{volume of the section of the pipeline}} \tag{4}$$

Its value varies from zero for gases to one for liquids. Numerous methods have been developed to compute ϖ_l. The Beggs-Brill method is implemented in the *OptiRamp* multiphase flow model to compute ϖ_l because it is one of the most reliable and robust methods of predicting the liquid holdup in nearly vertical wells and in hilly-terrain pipelines.

The Beggs-Brill method employs the flowing procedure to determine ϖ_l. First, the liquid content $\lambda_l = \frac{v_l}{v_l + v_g}$ and Froude number $N_{Fr} = \frac{(v_l + v_g)^2}{gD}$ of the multiphase fluid are determined. Those values are then used to identify the flow regime (i.e., the qualitative characteristics of the

flow of the fluid through the pipe). Finally, the flow regime, the liquid content, and the Froude number are used in equation (5) to compute the liquid holdup,

$$\varpi_l = \left[1 + \beta\left(\sin(1.8\theta) - \tfrac{1}{3}\sin^3(1.8\theta)\right)\right] \times \left[a\frac{(\lambda_l)^b}{(N_{Fr})^c}\right], \tag{5}$$

where a, b, and c are experimentally determined parameters that have different values for each flow regime and β is an empirical function of λ_l, N_{Fr}, the flow regime, and the sign of θ.

Under the Beggs-Brill method, multiphase fluid flow through the pipe is assigned to one of the following regimes:

- Segregated Flow: liquid and gas phases are separated from one-another and move (mostly) independent of each other; furthermore, the relative amount of volume each phase occupies remains fairly constant
- Intermittent Flow: liquid and gas phases are separated from one-another; however, the relative volumes of the liquid and gas phases fluctuate, coupling their motions
- Distributed Flow: liquid and gas phases are mixed together and move collectively
- Transitional Flow: liquid/gas mixture is transitioning between two of the regimes listed above

Figure 1 visually represents segregated, intermittent, and distributed flow. Figure 2 displays the flow regime map used to determine the flow regime.

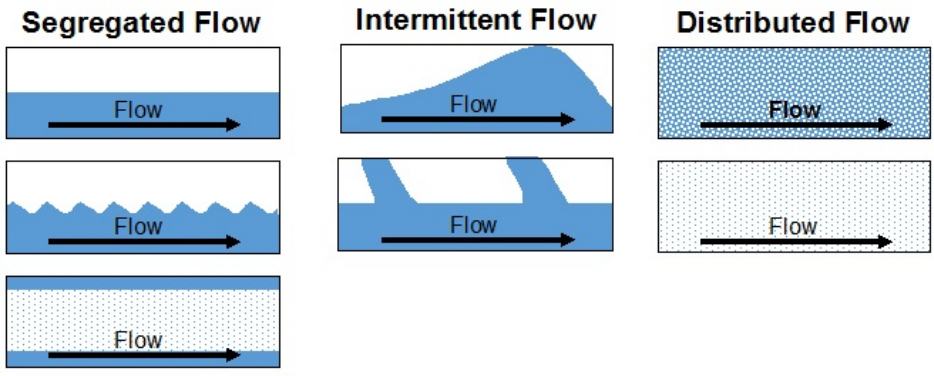

Figure 1. Visual representations of the segregated, intermittent, and distributed flow regimes

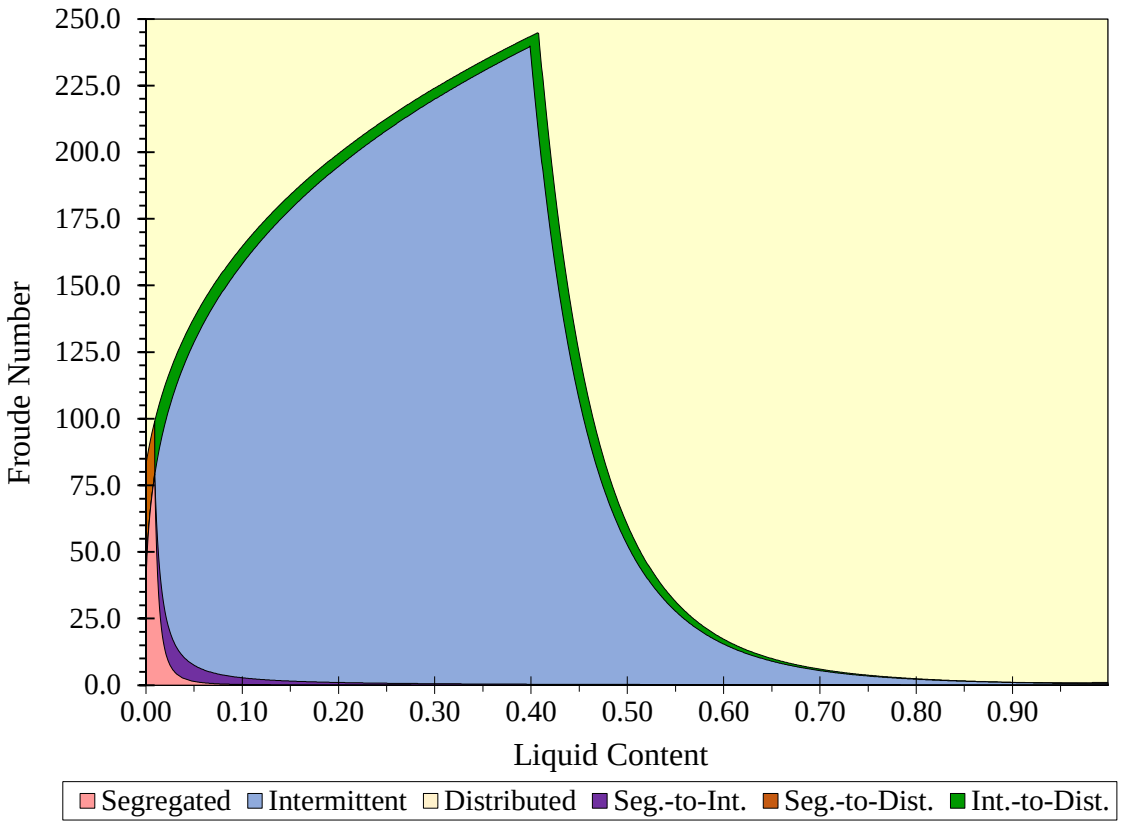

Figure 2. Regime classification map that determines the flow regime of the flow a multiphase fluid through a pipe

Empirical Parameters

In general, simple averaging techniques cannot be used to determine the changes that will occur in empirical parameters that depend on the nature of the fluid. Consider the friction factor, the simplest method of determining *f* would be to compute it directly from the Colebrook equation using the molecular properties of the multiphase system. Unfortunately, studies have shown that reliable predictions of the changes in multiphase fluid mass flow rate and thermodynamic properties cannot be obtained when the friction factor is determined directly from the Colebrook equation. Instead, a more reliable value for the friction factor should be obtained by multiplying the value for *f* determined from the Colebrook equation by an empirically calculated correction, $f_{Multiphase} = f_{Colebrook} \times C$.

The Beggs-Brill method is also used by the *OptiRamp* multiphase flow model to determine the friction factor. Under that method, the no-slip friction factor f_{NS} is multiplied by the exponential of $S(\lambda_l, \varpi_l)$, an empirically determined function of λ_l and ϖ_l, shown in equation (6)

$$f_{BB} = f_{NS} e^{S(\lambda_l, \varpi_l)} \tag{6}$$

The no-slip friction factor is the friction factor computed from the Colebrook equation using the no-slip values of the molecular properties. No-slip values for molecular properties are obtained using λ_l (in place of ϖ_l) when averaging the gas and liquid phase values of the corresponding molecular properties.

Mechanical Characteristic Curves

Typically, it is difficult to predict the efficiency and power requirements for industrial equipment designed to handle single-phase fluids (e.g., gas compressors, liquid pumps, etc.) when the equipment operates on a multiphase fluid. To reduce the impact of those errors (and other errors) a self-learning algorithm is incorporated into the *OptiRamp* flow model. The self-learning algorithm adjusts some of the empirical parameters that are used in the model to reduce the deviation that is observed between the calculated and experimentally measured values for $\dot{m}$, P, and T.

Modeling the Performance of a Deep-Water Oil Field Pipeline

The *OptiRamp* multiphase flow model was used to simulate performance of an existing industrial pipeline to prove its reliability. The pipeline pumps oil, water, and gas out of a deep-water oil field through multiple oil wells. The oil/water/gas mixtures obtained from each well are directed to a transportation pipeline, where they are combined and delivered to a nearby floating production unit. The floating production unit merges the four oil/water/gas mixtures into a single stream of fluid and pumps that fluid into a separation tank, where the oil, water, and gas components of the fluid are separated from one another. The oil and gas are transported to an onshore refinement facility. The water undergoes additional purification and is released into the ocean. A schematic diagram of the pipeline is shown in Figure 3.

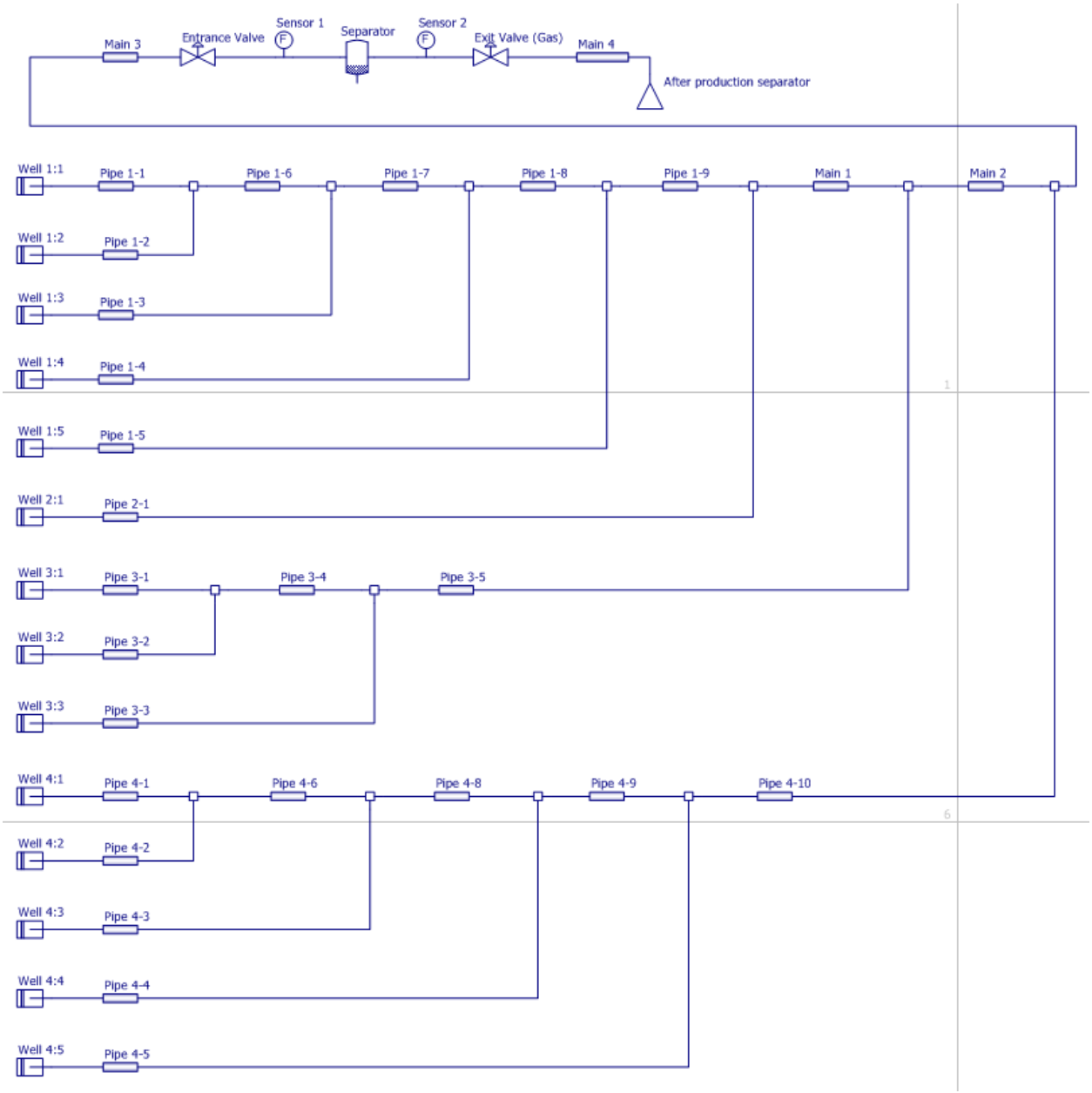

Figure 3. A schematic diagram of the industrial pipeline that is being modeled.

The section of the pipeline being modeled follows the multiphase fluid as it is drawn out of each of the oil wells and directed to the separation unit. The remainder of the pipeline was not explicitly modeled. While passing through the modeled pipeline section, the fluid encounters control valves, measuring devices, areas of gradual uphill flow, areas of nearly vertical flow, and multiple T-junctions. The calculation results are also highly dependent on the formulas that were used to model the properties of each oil-well. During the time interval being simulated, there were 14 active oil wells.

To assess the simulation accuracy, experimentally measured values of the downstream pressure of each oil well and the oil, water, and gas volumetric flow rates of each oil well were compared to the values calculated by the *OptiRamp* multiphase flow model. The volumetric flow rates are shown in Table 1. The downstream pressures are shown in Table 2. Simulated and experimentally measured volumetric flow rates for the oil, water, and gas that exited the separator were also compared to each another. Those values are also displayed in Table 1. The experimentally measured pressures and flow rates were observed on Oct. 9, 2015.

Oil field blueprints were used to identify the distances, diameters, thicknesses, and changes in elevation of each pipe. The initial composition of the liquid mixture that was produced from each oil well was determined experimentally. When available, experimentally values were used to specify the chemical properties of each liquid mixture (in all cases the initial oil and water densities were determined experimentally). Commonly observed values were used for the chemically properties that were not experimentally measured.

Table 1. Volumetric flow rates for the deep-water oil field pipeline, in bbl/d

Oil Well	Oil Component			Water Component			Gas Component		
(Pad:Well)	Model	Exp.	% Error	Model	Exp.	% Error	Model	Exp.	% Error
1:1	27.7	27.6	0.38	220.5	219.7	0.37			
1:2	310.2	309.6	0.21	459.2	458.2	0.21			
1:3	4.0	4.0	1.61	58.1	57.2	1.60	4.09	4.03	1.61
1:4	79.4	79.4	0.00	223.5	223.6	-0.01			
1:5	97.6	97.0	0.65	767.5	762.8	0.62			
2:1	137.3	137.5	-0.12	25.5	25.6	-0.15			
3:1	142.3	142.5	-0.15	10.7	10.7	-0.11			
3:2	186.5	185.0	0.82	115.5	114.6	0.83			
3:3	535.0	546.5	-2.09	575.0	587.3	-2.10			
4:1	38.4	37.9	1.30				14.76	14.57	1.30
4:2	17.0	17.2	-0.93	145.2	146.6	-0.97			
4:3	717.5	731.9	-1.96	15.9	16.3	-2.12	2.06	2.10	-1.96
4:4	825.7	816.7	1.10	9.3	9.1	1.41			
4:5	20.4	20.2	1.36				11.80	11.64	1.36
Separator	3103	3153	-1.57	2655	2632	0.90	31.96	32.34	-1.19

Table 2. Downstream pressures for each oil well, in psig.

Oil Well (Pad:Well)	Model	Exp.	% Error
1:1	149.3	156.0	-4.31
1:2	151.7	157.0	-3.41
1:3	149.3	155.0	-3.70
1:4	149.3	157.0	-4.92
1:5	147.8	155.0	-4.65
2:1	175.4	153.0	14.65
3:1	173.6	155.0	12.02
3:2	148.5	153.0	-2.97
3:3	177.8	152.0	16.97
4:1	158.0	152.0	3.97
4:2	146.3	153.0	-4.38
4:3	147.5	154.0	-4.21
4:4	175.4	155.0	13.17
4:5	149.6	147.0	1.75

The simulation results found that for all oil wells and for the separator, the predicted volumetric flow rate values are within 2.1% of the values that were reported experimentally. Likewise, for 11 of the oil wells, the predicted downstream pressure values agree to within 5% of the values measured experimentally. The average percent errors of the predicted volumetric flow rate and downstream pressure values were 1.00% and 7.18%, respectively.

Conclusion

In this paper, we discussed the concerns that must be addressed to accurately simulate the transportation of oil/water/gas mixtures across pipelines. The paper describes the equations used by the *OptiRamp* simulation software to model complex multiphase flow processes and demonstrates that the *OptiRamp* simulation software can accurately predict pipeline behavior.

About Statistics & Control, Inc.

S&C—an engineering consulting and technology company headquartered in West Des Moines, IA—solves complex challenges for customers through its unique technology and its highly seasoned team of professionals. The company has a global portfolio spanning the energy, oil and gas, utility, and digital oil field industry sectors. S&C provides clients with turbomachinery control solutions that easily integrate with the existing system as well as *OptiRamp*® solutions, which focus on process and power analytics to optimize processes and, in turn, reduce costs and increase reliability. S&C also provides consulting, dynamic system studies, modeling, automation, training and OTS, and support services.

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