PSIG 1626

Real-Time Simulation System

Vadim Shapiro[1], Daniel P. Theis[1]

[1] Statistics & Control

This paper was prepared for presentation at the PSIG Annual Meeting held in Vancouver, British Columbia, 11 May – 13 May 2016.

ABSTRACT

This paper reviews the physical and practical considerations that need to be addressed to develop an accurate and robust computational model of the transportation of multiphase fluids across large-scale pipelines. It then demonstrates the accuracy of the *Real-Time Simulation System*, which was designed according to the scientific principles that are laid out in the paper. To demonstrate the accuracy of the model, computed pressures, temperatures, and mass flow rates along a commercial pipeline are compared against experimentally measured values.

INTRODUCTION

Pipelines in oil and gas production systems normally transport multiphase mixtures of oil, water, and gas. Simulation of complex multiphase flow processes is an important aspect of efficient oil field operation. Safety and optimization rely on a detailed understanding of multiphase flow behavior.[1]

The multiphase flow model that is built into the simulation software employs conservation laws and well-established empirical formulas to simulate the changes that occur to the mass flow rate and thermodynamic properties (pressure, temperature, *etc.*) of single or multiphase fluids that are transported across industrial scale pipelines.[2,3] A diverse set of equations of state are accessed by the model to simulate a wide variety of materials and to ensure that the model can handle the difficulties that arise from fluid compression and phase transitions.[4,5,6] When modeling the transportation of water/steam mixtures (that do not include contributions from oils or other gases), the multiphase flow model also determines the change that will occur to the quality of the steam (*i.e.* the composition of the water/steam mixture).

SCIENTIFIC FOUNDATION

Multiphase flow processes involve a combination of materials having different properties and often exhibit relative motion among the phases.[1,2] 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 those 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[4-6] 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. The specific algorithms that are used at a given point of the pipeline are chosen to account for the dominant forces that effect the properties of the fluid 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: the conservation of mass; the conservation of momentum; and the conservation of energy.[2,3] The conservation of mass dictates that matter cannot be created or destroyed. For the flow of a fluid through a pipe, this law can be expressed as:

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

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 the thermal expansion of the pipe is ignored, Eq. 1 indicates that the change in the mass flow rate along the direction of the pipe can be determined from the rate of

change of the density, $\frac{\partial \dot{m}}{\partial x} = -A\frac{\partial \rho}{\partial t}$.

The conservation of momentum determines the change that occurs to the momentum of the fluid due to the forces that are directed towards or against the direction of its flow. When a fluid flows through a pipe three forces effect its movement: gravitational force F_{grav}; frictional force F_{Fric}; and the force this is produced from the pressure gradient of the fluid $F_{\nabla P}$. Based on the conservation of momentum, the following expression will determine the combined influence that those three forces have on the fluid's momentum,

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

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, $N_{Re} = \frac{v\rho D}{\mu}$ 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.[7]

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 the energy changes within a small segment of the pipe is equal to the change in energy that is due to the movement of the fluid through the pipe minus the sum of the amount of energy that is used to compress the fluid and the amount of heat that is dissipated through the wall of the pipe into the surrounding environment. Mathematically, that relationship is expressed by the following equation:

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

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 pipe. Eq. 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.[8]

Based on Eqs. 1 – 3, finite difference algorithms were developed for the multiphase flow model that separate the time into small time steps and separate the length of each pipe into small pipe segments.[9] 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 Eqs. 1 – 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 that are shown in Eqs. 1 – 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 that are 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 that is connected to the pipeline.[10,11] Empirical formulas are also used to predict the properties of the fluid at its source[12] (*i.e.* at the oil production wells, steam generators, *etc.*).

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

When T-junctions are encountered that merge two fluid streams into one, 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.[4,5] At T-junctions that distributed 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.[2,3]

Modeling the Flow of Multiphase Fluids

When designing a multiphase flow model, it is important to carefully consider each algorithm that is used and determine whether or not it depends on the nature of the fluid. For instance, the conservation laws are universal and will describe the motion of any type of fluid, including multiphase fluids. Only the formulas that are used to evaluate the molecular

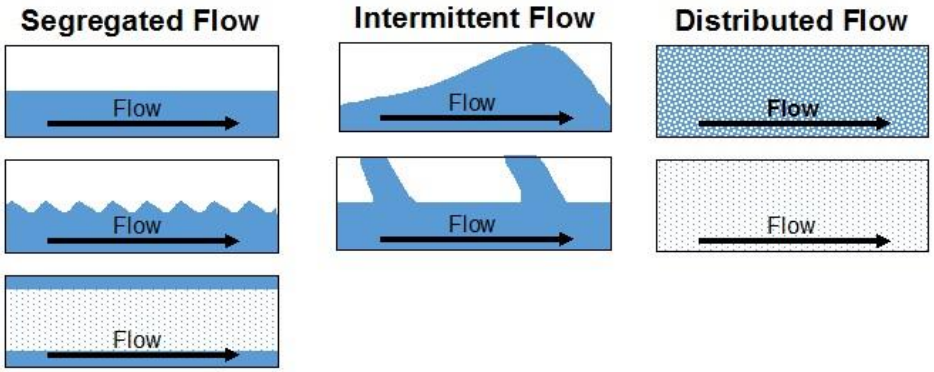

Figure 1. Visual representations of the segregated, intermittent, and distributed flow regimes.

properties and the friction factor need to be modified.[10] Likewise, the empirical parameters that are needed to calculate the sudden changes to $\dot{m}$, P, and T at each pipe fitting do not depend on the properties of the fluid, this means that the formulas that depend on those parameters do not needed 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 that are 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,

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

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 multiphase flow model to compute ϖ_l. The Beggs-Brill method is used 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[13] 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 the following expression to compute the liquid holdup,

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

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 the flow of a multiphase fluid through the pipe is assigned to one of the following regimes:

- ***Segregated Flow***, the liquid and gas phases are separated from one-another and move (mostly) independent of each other. Furthermore, the relative amount of volume that each phase occupies remains fairly constant.
- ***Intermittent Flow***, the 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***, the liquid and gas phases are mixed together and move collectively.
- ***Transitional Flow***, the liquid/gas mixture is transitioning between two of the regimes listed above.

Figure 1 gives a visual representation of segregated, intermittent, and distributed flow. **Figure 2** displays the flow regime map that is used to determine the flow regime.

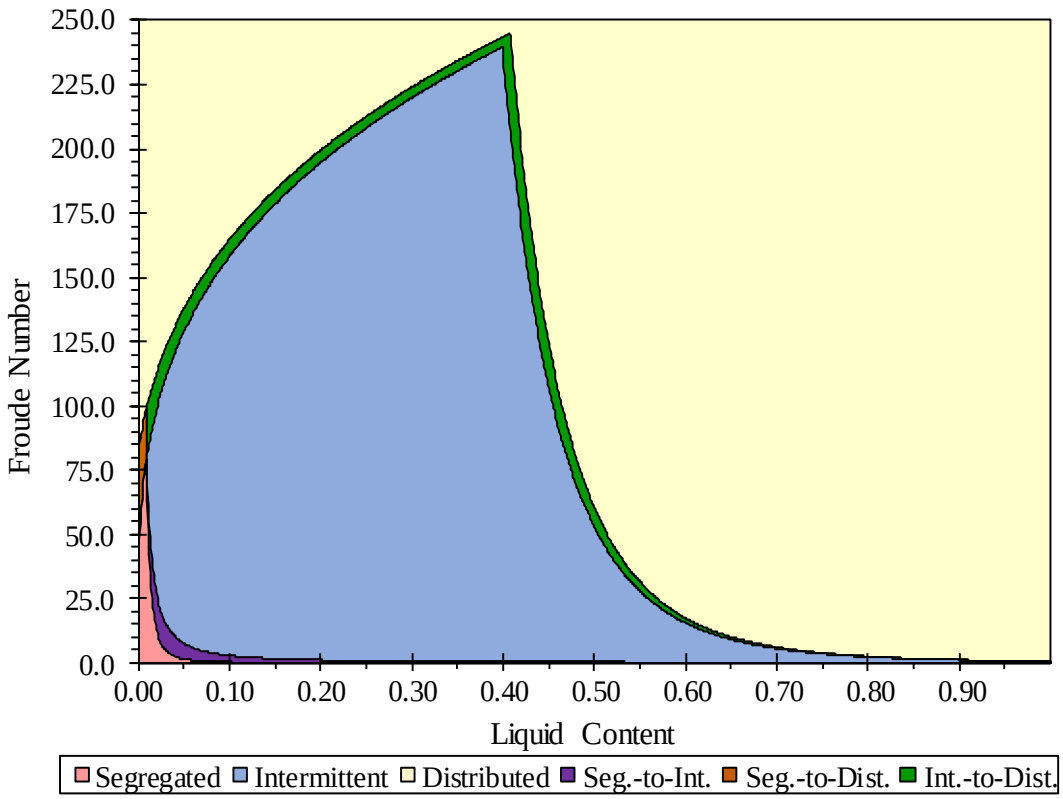

Figure 2. The regime classification map that determines the flow regime.

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 the mass flow rate and thermodynamic properties of multiphase fluids cannot be obtained when the friction factor is determined directly from the Colebrook equation.[14] Instead, a more reliable value for the friction factor should be obtained by multiplying the value for f that was determined from the Colebrook equation by an empirically calculated correction, $f_{Multiphase} = f_{Colebrook} \times C$.

Under the Beggs-Brill 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,[13]

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

The no-slip friction factor is the friction factor that is computed from the Colebrook equation using the no-slip values of the molecular properties. No-slip values for molecular properties are obtained by 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 that is designed to handle single-phase fluids (*i.e.* 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 used alongside the multiphase flow model. The self-learning algorithm adjusts some of the empirical parameters that are used by the multiphase flow model to reduce the deviation that is observed between the calculated and experimentally measured values for $\dot{m}$, P, and T.

CASE STUDY: DEEP-WATER OIL FIELD PIPELINE

To demonstrate the reliability of the multiphase flow model, it was used to simulate the performance of an existing industrial pipeline. The pipeline in question pumps oil, water, and gas out of a deep-water oil field through multiple oil wells. The oil/water/gas mixtures that are obtained from each well are directed to 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 on-shore refinement facility. The water undergoes additional purification and is released into the ocean. A schematic diagram of the pipeline is shown in **Figure 3**.

The section of the pipeline that is 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 section of the pipeline that was modeled, the fluid encounters control valves, measuring devices, areas of gradual uphill flow, areas of nearly vertical flow, and multiple T-junctions. The results of the calculation are also highly dependent on the formulas that were used to model the properties of each oil-well. During the time interval that was being simulated there were 14 active oil wells.

To assess the accuracy of the simulation, experimentally measured values of the downstream pressure of each oil well and the oil, water, and gas volumetric flow rates of each oil

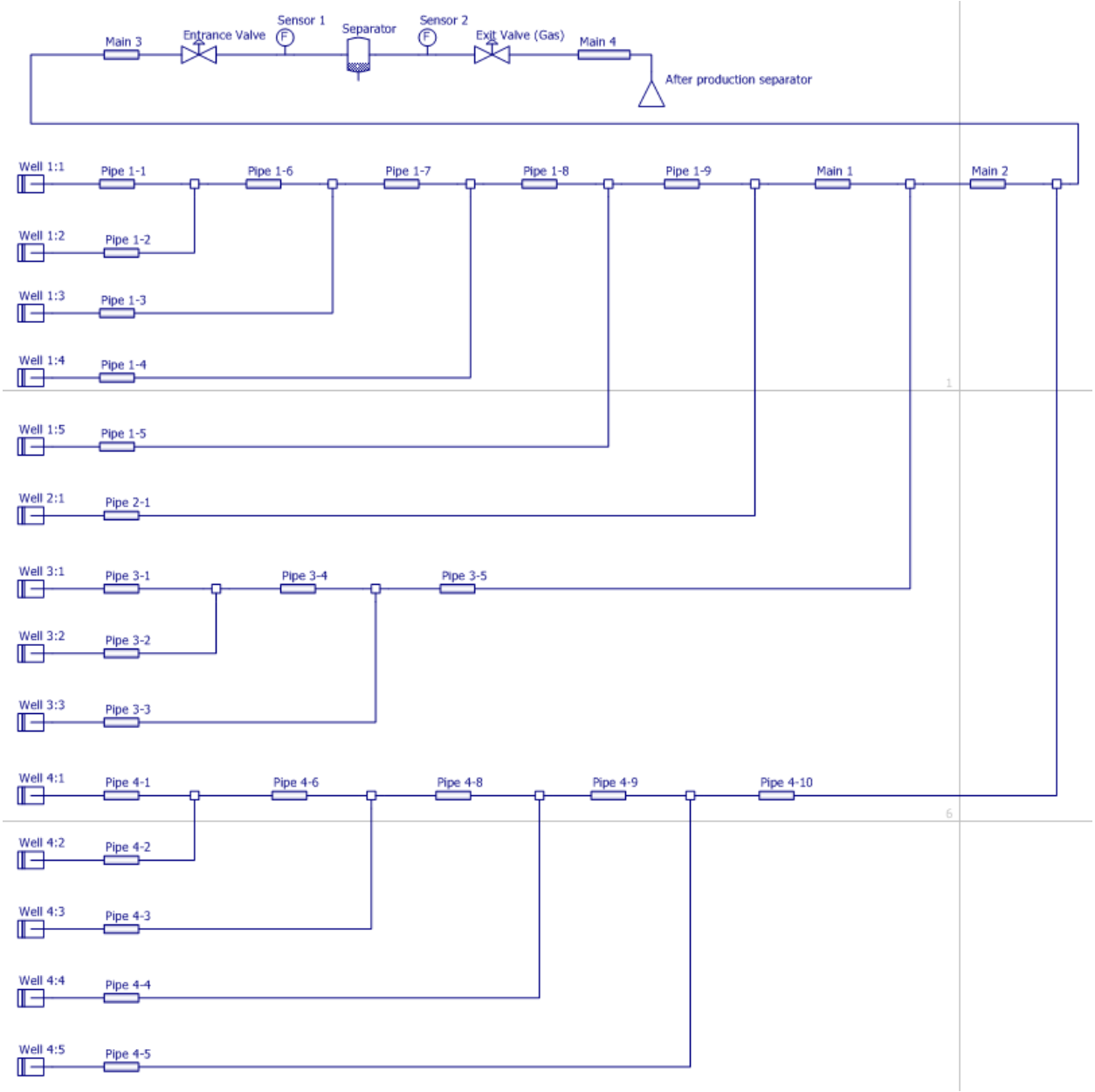

Figure 3. A schematic diagram of the industrial pipeline that is being modeled.

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

well were compared to the values that were calculated by the 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 chemical properties that were not experimentally measured.

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

CONCLUSIONS

This paper discussed the concerns that must be addressed to accurately simulate the transportation of oil/water/gas mixtures across pipelines. Included in that discussion was a review of the fundamental conservation laws that govern the flow of single-phase fluids and a description of the empirical corrections that need to be included when modeling the flow of multiphase fluids. The final section of the paper demonstrated the accuracy of a simulation program, which was developed using the principles that were discussed in the paper.

REFERENCES

1. W. C. Lyons, *Standard Handbook of Petroleum and Natural Gas Engineering Vol. 1 and 2*, (Gulf Publishing Co., Houston, 1996).
2. M. V. Lurie, *Modeling of Oil Product and Gas Pipeline Transportation*, (WILEY-VCH Verlag GmbH & Co., Winheim, 2008).
3. H. D. Beggs, *Gas Production Operations*, (Oil & Gas Consultants International Inc., Tulsa, 1984).
4. M. R. Riazi, *Characterization and Properties of Petroleum Fractions*, (ASTM International, West Conshohocken, 2005).
5. W. D. McCain Jr., *The Properties of Petroleum Fluids*,

2nd Ed., (PennWell Publishing Co., Tulsa, 1990).

6. J. R. Cooper and R. B. Dooley, *Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam*, (International Association for the Properties of Water and Steam, Lucerne, 2007).
7. C. F. Colebrook, *J. Fluid Eng.*, **105**, 89 (1983).
8. M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodyanics, 5th Ed*., (John Wiley & Sons Inc., West Sussex, 2006).
9. S. V. Patankar, *Numerical Heat Transfer and Fluid Flow*, (Hemisphere Publishing Co., New York, 1980).
10. A. P. Szilas, *Production and Transport of Oil and Gas, 2nd Completely Revised Ed*., (Elsevier, New York, 1986).
11. T. Wright, *Fluid Machinery: Performance, analysis, and Design*, (CRC Press, New York, 1999).
12. Z. Chem, *Reservoir Simulation: Mathematical Techniques in Oil Recovery*, (Society for Industrial and Applied Mathematics, Philadelphia, 2007).
13. D. H. Beggs and J. P. Brill, *J. Petro. Tech*. **25**, 607 (1973).
14. *See* O. Baker, *Oil and Gas J*. **Nov. 11**, 150 (1957) *and the references within*.

AUTHOR BIOGRAPHY

Vadim Shapiro,
Statistics & Control, Inc., President

Vadim Shapiro is co-founder and President of *Statistics & Control, Inc*. He manages all aspects of engineering, including development of the company's *OptiRamp*® Advanced Process Control software. Vadim Shapiro has over 20 years' leadership experience in systems and software engineering, project management, and product development in the field of turbo machinery control, advanced process control, and power management systems. Vadim Shapiro holds six patents in the area of turbomachinery control and advanced process control, with several applications pending.

Dr. Daniel P. Theis,
Statistics & Control, Inc., Software Engineer

Daniel P. Theis is a software engineer working at *Statistics & Control, Inc*. He holds a B.Sc. (2003) in Chemistry, a M.Sc. (2006) in Physical Chemistry, and a Ph.D. (2011) in Computational Chemistry. Dan Theis has over 10 years' experience in the development and use of computer software that is designed to predict the properties and behavior of complex chemical systems.