

A Study of Terrain-Induced Slugging in Pipelines Using Aspen Hydraulics Within Aspen HYSYS[®] Upstream

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Introduction

In pipeline gathering networks, slug formation can present issues in the operation of pipelines and downstream equipment. To increase pipeline efficiency and prevent damage to equipment, action needs to be taken to prevent slug formation. Slug catchers also need to be implemented to remove slugs prior to gas processing.

In the upstream oil and gas industry, slug flow remains an important challenge as gas and liquids are moved across the gathering network. Slug flow can occur in several forms:

- Terrain-induced slugging
- Hydrodynamic slugging
- Severe slugging
- Pig-induced slugging

Terrain-induced slugs are caused by the accumulation and periodic pushing of liquid along the pipeline. This type of slug is common at the local minima of the pipeline network. As liquid accumulates at the slug point, pressure begins to build upstream. When pressure builds up enough, the accumulated liquid is pushed uphill, resulting in a slug. When the liquid is pushed out of the minimum, the pressure drops, liquid begins accumulating again and the cycle continues¹. For an illustration of each stage of terrain-induced slugging, see Figure 1.

Hydrodynamic slugging is caused by differences in the velocities of the gas and liquid phases in a two-phase flow. When the relative velocity between the two phases is sufficiently large, waves can form on the surface of the liquid. When the amplitudes of these waves become large enough, they can bridge the diameter of the pipe, resulting in liquid slugs².

Severe slugging is similar in nature to terrain-induced slugging in that it involves the periodic buildup of liquid at low points in the pipeline. The primary difference between severe slugging and regular terrain-induced slugging is that severe slugging occurs at risers³.

Pig-induced slugging is caused by devices, known as pigs, that may be inserted into pipelines to perform a variety of tasks, including cleaning and data collection. When a pig moves through the pipeline at a velocity greater than that of the liquid phase in front of it, the liquid will accumulate in front of the pig, resulting in slug formation.

This white paper will focus on terrain-induced slugging, the challenges in predicting this type of slugging, the solutions available for addressing these challenges and the benefits of using this solution.

Supporting Aspen HYSYS® files are available on the [AspenTech Support Website](#) by searching for the title "White Paper and Demo Files: Predict and monitor terrain-induced slugging in the pipeline."

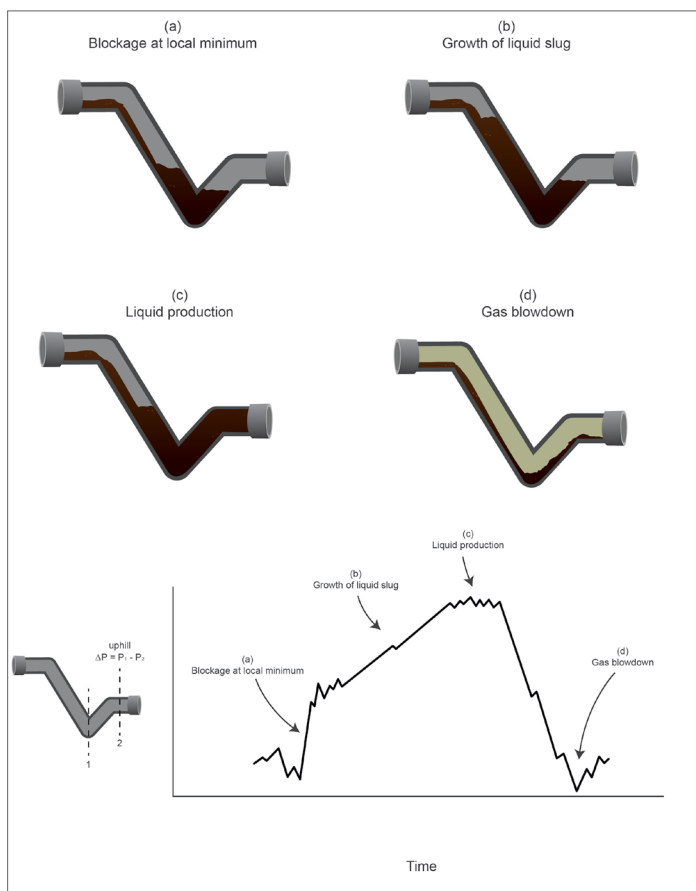


Figure 1. Example of terrain-induced slugging

Challenges

In the operation of pipelines, production and asset utilization need to be maximized for product flow while balancing the cost of compressors and maintenance. Environmental regulations need to be consistently met. Production engineers need to size transport pipes so they transport close to maximum production throughout the life of the well. If the pipeline is oversized, especially later in the life of the field, it may cause terrain-induced slugging in the pipes⁴. The slug flow may jeopardize mechanical integrity and cause excessive corrosion, making the production uneconomical.

When designing a new pipeline network or upgrading an existing pipeline, several studies should be considered in order to achieve an accurate and precise design of multiphase flow lines. These studies include pigging, ramp-up and ramp-down analysis, shut-down studies, slugging, slug volume calculation, hydrate formation, wax deposition, and asphaltene deposition.

Multiphase flow is intrinsically unstable and as it moves through a pipeline over time, it experiences differences in elevation, friction and obstruction. Dynamic simulation is then needed for predicting liquid holdup, temperature and pressure profiles over distances⁵.

Solution

Aspen Hydraulics is a tool available in Aspen HYSYS® Upstream for modeling pipeline networks in steady-state and dynamics mode. In dynamic simulations, Aspen Hydraulics solves the governing partial differential equations for two-phase flow (shown below) to predict the evolution of flow in a pipeline, including terrain-induced slugging. For more information about each variable, please refer to the appendix at the end of this paper.

Gas Mass Conservation

$$\frac{\partial(\alpha\rho_g)}{\partial t} + \nabla \cdot (\alpha\rho_g\vec{V}_g) = \Gamma$$

Liquid Mass Conservation

$$\frac{\partial[(1-\alpha)\rho_l]}{\partial t} + \nabla \cdot [(1-\alpha)\rho_l\vec{V}_l] = -\Gamma$$

Gas Momentum Conservation

$$\frac{\partial\vec{V}_g}{\partial t} + \vec{V}_g \cdot \nabla\vec{V}_g = -\frac{1}{\rho_g}\nabla p - \frac{c_i}{\alpha\rho_g}(\vec{V}_g - \vec{V}_l)|\vec{V}_g - \vec{V}_l| - \frac{\Gamma^+}{\alpha\rho_g}(\vec{V}_g - \vec{V}_l) - \frac{c_{wg}}{\alpha\rho_g}\vec{V}_g|\vec{V}_g| + \vec{g}$$

Liquid Momentum Conservation

$$\frac{\partial\vec{V}_l}{\partial t} + \vec{V}_l \cdot \nabla\vec{V}_l = -\frac{1}{\rho_l}\nabla p + \frac{c_i}{(1-\alpha)\rho_l}(\vec{V}_g - \vec{V}_l)|\vec{V}_g - \vec{V}_l| - \frac{\Gamma^-}{(1-\alpha)\rho_l}(\vec{V}_g - \vec{V}_l) - \frac{c_{wl}}{(1-\alpha)\rho_l}\vec{V}_l|\vec{V}_l| + \vec{g}$$

Total Energy Conservation

$$\frac{\partial[(1-\alpha)\rho_l e_l + \alpha\rho_g e_g]}{\partial t} + \nabla \cdot [(1-\alpha)\rho_l e_l \vec{V}_l + \alpha\rho_g e_g \vec{V}_g] = -p\nabla \cdot [(1-\alpha)\vec{V}_l + \alpha\vec{V}_g] + q_{wl} + q_{wg}$$

Gas Energy Conservation

$$\frac{\partial(\alpha\rho_g e_g)}{\partial t} + \nabla \cdot (\alpha\rho_g e_g \vec{V}_g) = -p\frac{\partial\alpha}{\partial t} - p\nabla \cdot (\alpha\vec{V}_g) + q_{wg} + q_{ig} + \Gamma h_{sg}$$

Visualizing and Collecting Data in Aspen HYSYS

Aspen HYSYS and Aspen Hydraulics provide several ways to observe pipeline data. Every pipe segment in Aspen Hydraulics contains a profile that's accessed from the performance tab of the pipe form. The profile reports the values of certain key properties (such as temperature, pressure, velocity and liquid holdup) along the length of the pipe, as well as the elevation profile of the pipe. The number of points included in the profile is determined based on the number of pipe cells specified on the design/data page. A larger number of cells will provide finer details in the pipe profile but at a higher computational cost. The profile data can be viewed in tabular form or in one of eight automatically generated plots.

Distance [ft]	Elevation [ft]	Pressure [psia]	Temperature [F]	Mean Velocity [ft/s]	Vap. Velocity [ft/s]	Liq. Velocity [ft/s]	Vap.
0.0000	0.0000	905.4	144.4	5.861	5.861	5.861	
200.0	-20.00	905.7	144.4	5.881	5.098	9.668	
400.0	-40.00	906.2	144.4	5.899	5.182	9.731	
600.0	-60.00	906.6	144.4	5.917	5.254	9.649	
800.0	-80.00	907.1	144.4	5.936	5.280	9.671	
1000	-100.00	907.4	144.4	5.955	5.276	9.739	
1100	-140.00	909.9	144.4	5.963	5.220	10.07	
1200	-180.00	912.5	144.5	5.960	5.191	10.02	
1300	-220.00	915.3	144.6	5.957	5.165	10.02	
1400	-260.00	918.6	144.6	5.953	5.201	9.212	
1500	-300.00	932.2	144.7	5.947	5.687	6.658	
1900	-280.00	928.1	145.2	5.910	7.635	4.167	
2300	-260.00	923.9	145.1	5.971	7.646	4.270	
2700	-240.00	919.5	145.1	6.033	7.443	4.632	
3100	-220.00	914.7	145.0	6.094	7.272	5.050	
3500	-200.00	912.0	144.9	6.154	7.367	5.221	
3560	-200.00	911.8	144.8	6.174	6.930	5.526	
3620	-200.00	911.7	144.8	6.181	6.913	5.556	
3680	-200.00	911.5	144.8	6.187	6.913	5.571	
3740	-200.00	911.4	144.8	6.194	6.916	5.584	
3800	-200.00	911.2	144.8	6.201	6.921	5.594	

Figure 2. Aspen Hydraulics pipe profiles page

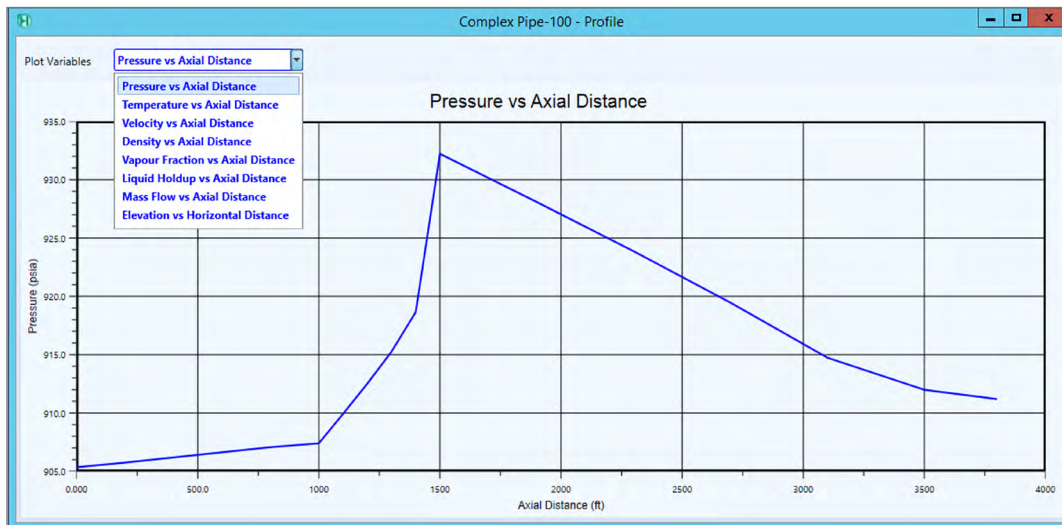


Figure 3. Aspen Hydraulics profiles plot

In addition to providing profiles of individual pipe segments, Aspen Hydraulics allows users to construct a combined profile based on a series of pipe segments. After the sequence of pipe segments has been selected, Aspen HYSYS can display the same tables and plots from the individual pipe profile for the combined pipe profile. For the case of a linear pipeline with no branching, this allows users to see the profile of the entire pipeline in one view, even when the pipeline contains multiple pipe segments.

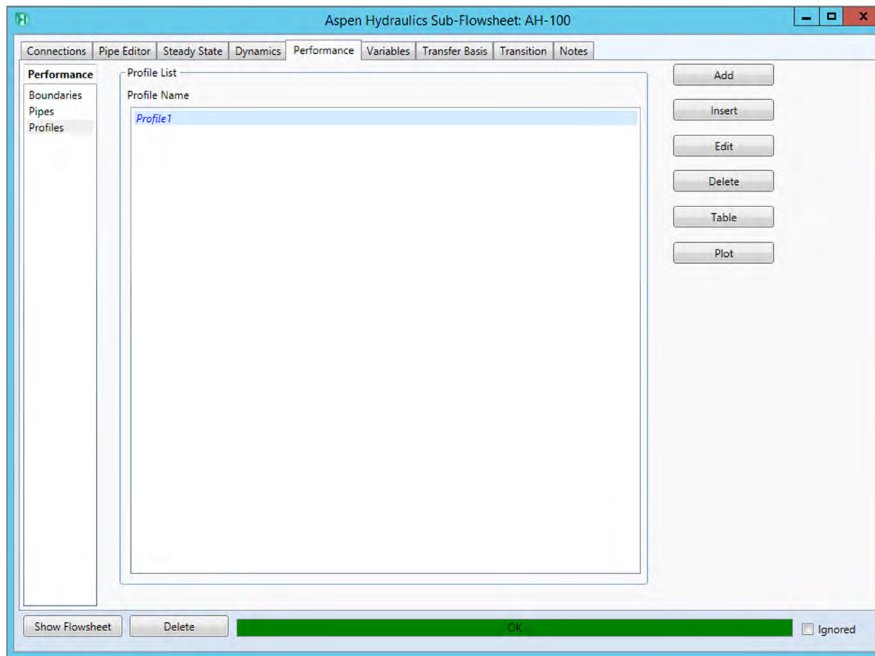


Figure 4. Aspen Hydraulics profile page

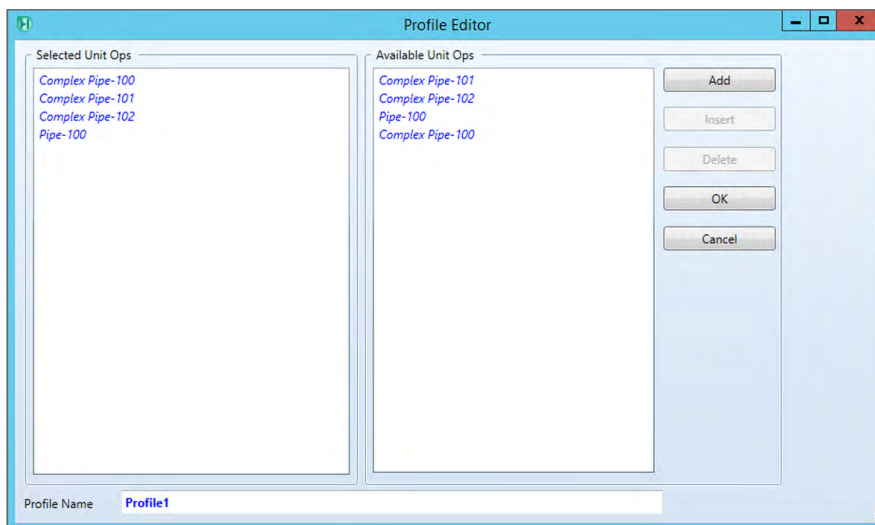


Figure 5. Aspen Hydraulics profile editor

A limitation of the pipe profile is that it can only display data for the current time point. The data is updated over the course of a dynamic simulation, so users can observe the profile plots to see how pipeline conditions change dynamically. However, the profiles do not store data from previous time points for later review.

In order to review data from previous time points, Aspen HYSYS offers the strip chart tool, accessible from the “Dynamics” ribbon and the navigation pane, for logging dynamic data. By utilizing the strip chart, users can specify which variables they are interested in tracking dynamically, so that resources are not wasted in tracking unimportant data. Variables (including data from the pipe profiles) can be added to the strip chart via the variable navigator by dragging and dropping, or by using the “send to” option from any form in Aspen HYSYS. Strip charts also allow users to choose how many historical data points to store and how frequently to record data from the dynamic simulation. The data collected by a strip chart can be visualized in Aspen HYSYS using customizable plots. Additionally, strip chart data is available in a tabular format that can be exported for analysis such as Microsoft Excel.

Time	Complex Pipe-100 - Liquid Flow at End of Incline [lb/hr]	Complex Pipe-100 Outlet - Phase Mass Flow (Liquid Phase) [lb/hr]	Complex Pipe-100 - Liquid Flow at Local Minimum [lb/hr]
15345.0	1.672e+005	8.419e+004	7.908e+004
15347.0	1.712e+005	9.991e+004	7.893e+004
15349.0	1.753e+005	1.251e+005	7.872e+004
15351.0	1.794e+005	1.511e+005	7.839e+004
15353.0	1.835e+005	1.694e+005	7.800e+004
15355.0	1.874e+005	1.825e+005	7.761e+004
15357.0	1.912e+005	1.920e+005	7.714e+004
15359.0	1.948e+005	1.991e+005	7.660e+004
15361.0	1.986e+005	2.050e+005	7.605e+004
15363.0	2.023e+005	2.097e+005	7.557e+004
15365.0	2.057e+005	2.136e+005	7.512e+004
15367.0	2.087e+005	2.168e+005	7.462e+004
15369.0	2.119e+005	2.202e+005	7.405e+004
15371.0	2.151e+005	2.233e+005	7.351e+004
15373.0	2.178e+005	2.259e+005	7.303e+004
15375.0	2.201e+005	2.279e+005	7.247e+004
15377.0	2.228e+005	2.304e+005	7.183e+004
15379.0	2.254e+005	2.328e+005	7.123e+004
15381.0	2.276e+005	2.347e+005	7.076e+004

Figure 6. Strip chart table of historical data

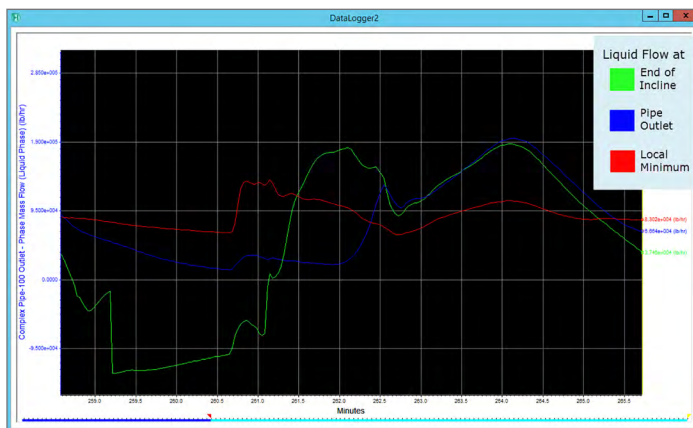


Figure 7. Strip chart plot

Case Study

In Aspen HYSYS, we have created a simple model representing a pipeline connecting the well to the outlet of the riser in dynamics mode.

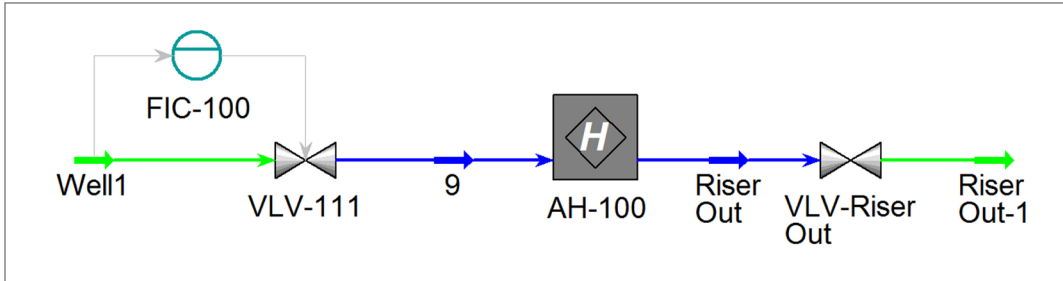


Figure 8. Aspen HYSYS main flowsheet

The well is modeled as a source with constant pressure, temperature and composition, with a flow rate determined by the pressure differential across VLV-111. On the opposite end of the pipeline, the outlet pressure in riser out-1 is set to a constant value.

The pipeline consists of several segments of piping with a riser at the end. The pipe lengths of each segment are as follows:

Pipe Segment	Length (ft)
Complex Pipe-100	3800
Complex Pipe-101	328.1
Complex Pipe-102	328.1
Riser	500

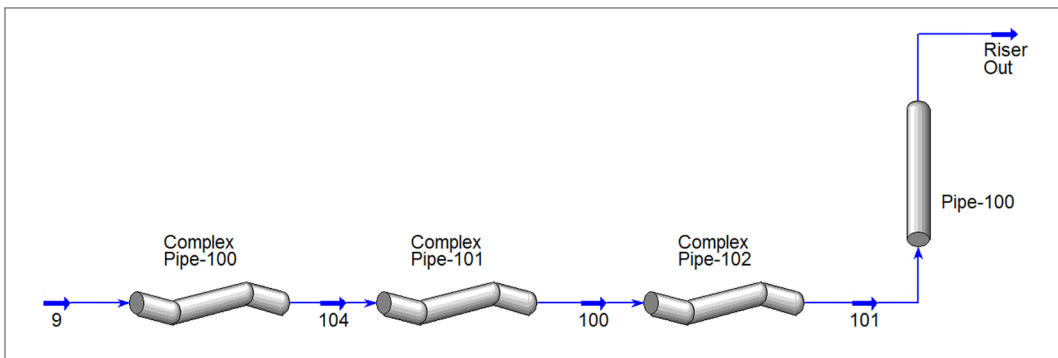


Figure 9. Aspen Hydraulics sub-flowsheet

From the Aspen Hydraulics sub-flowsheet summary view, you can create a pipeline profile, as shown in Figures 4 and 5. From there, we can see the elevation versus pipeline distance plot. In this pipeline, there is a local minimum at about 1,500 feet from the start of the pipeline where there is the potential for terrain-induced slugging to occur. Additionally, the pipeline ends with a riser where severe slugging may occur.

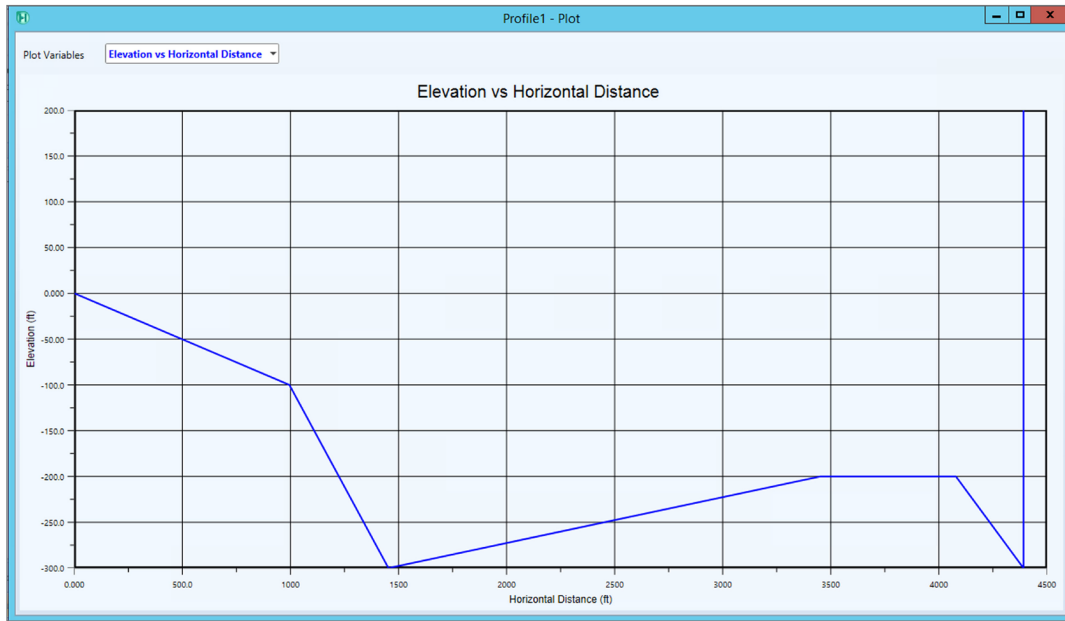


Figure 10. Aspen Hydraulics elevation profile

In the Aspen HYSYS simulation, strip charts were created to enable the observation of the slugging behavior. These strip chart results show the liquid mass flow rate at the outlet of the complex pipe-100 over time. This corresponds to an axial distance of 3,800 feet near the top of the incline following the first local minimum. In the plot, we can observe the liquid flow rate oscillating between periods of high and low liquid production.

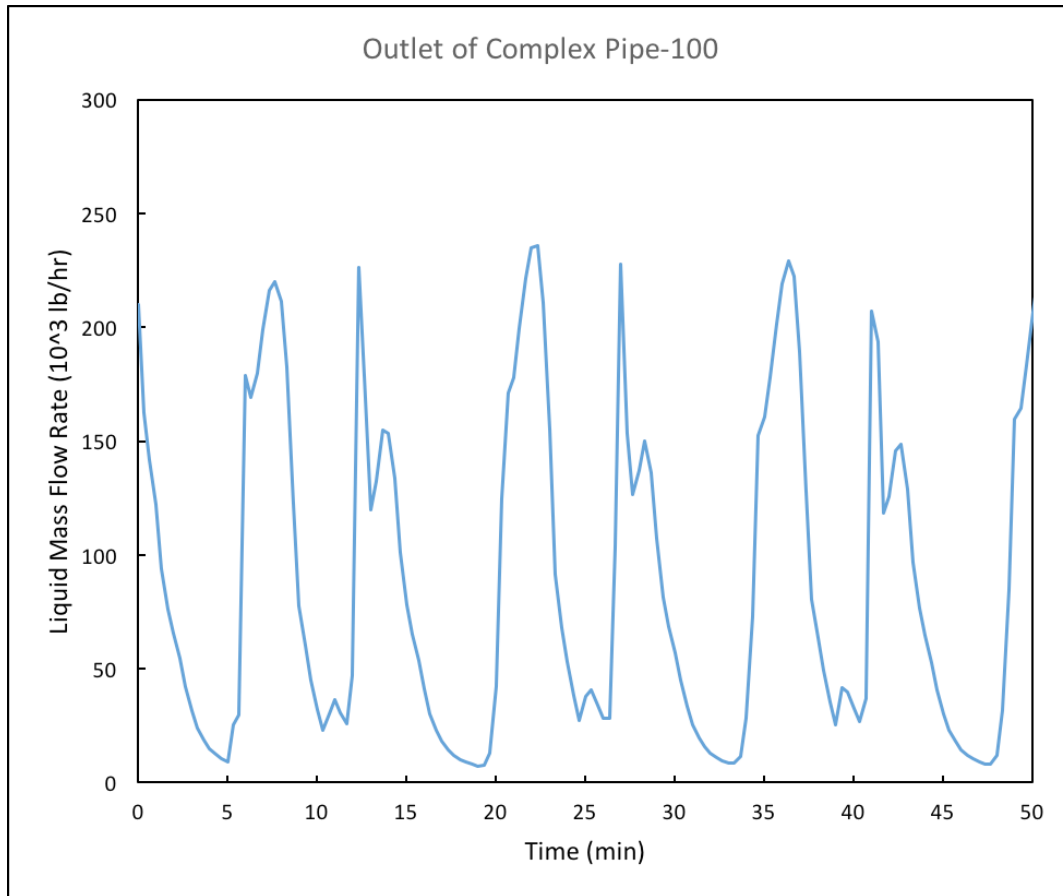


Figure 11. Liquid mass flowrate at 3,800 ft. of the pipeline

Additionally, we have taken snapshots of the profiles of complex pipe-100 at different stages of the terrain-induced slugging cycle. In the following plots, we can observe slug growth as the liquid velocity profile leads to accumulation in the uphill segment of the pipe (Figure 12). Liquid production occurs next, where the liquid velocity is positive over the entire uphill segment, into the horizontal plateau (Figure 13). The velocity then decreases from the peak liquid production (Figure 14), eventually returning to a point where the liquid begins to re-accumulate in the uphill segment (Figure 15).

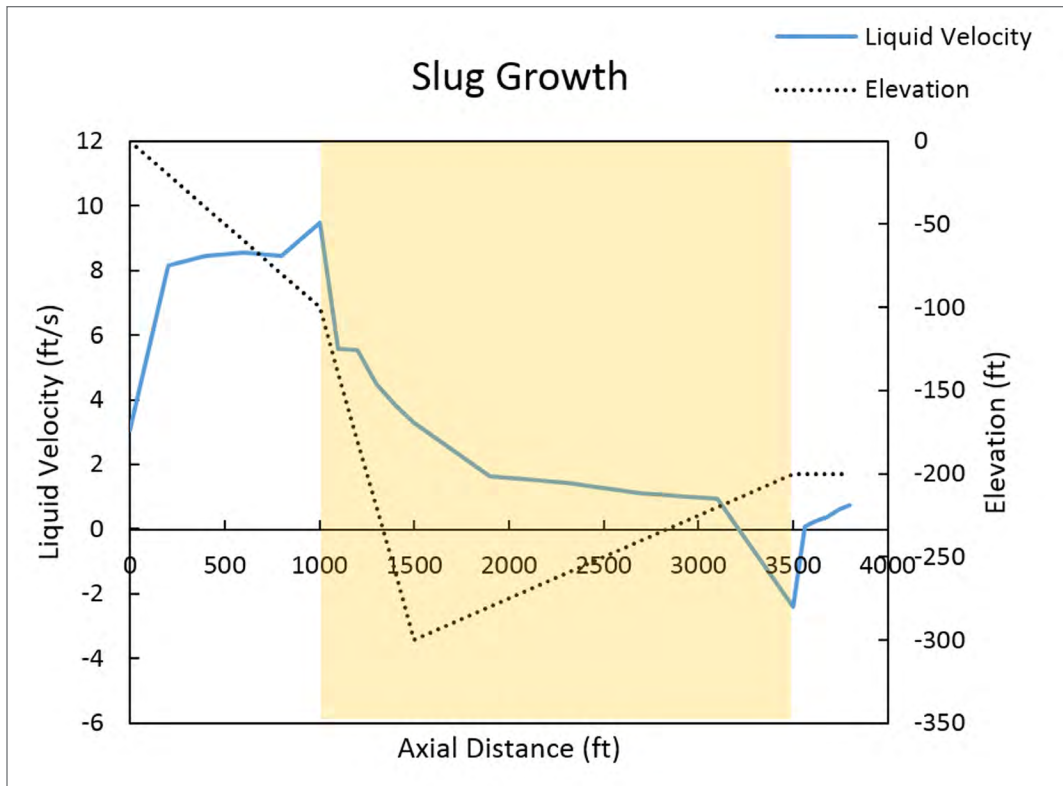


Figure 12. Liquid velocity and elevation profiles during slug growth

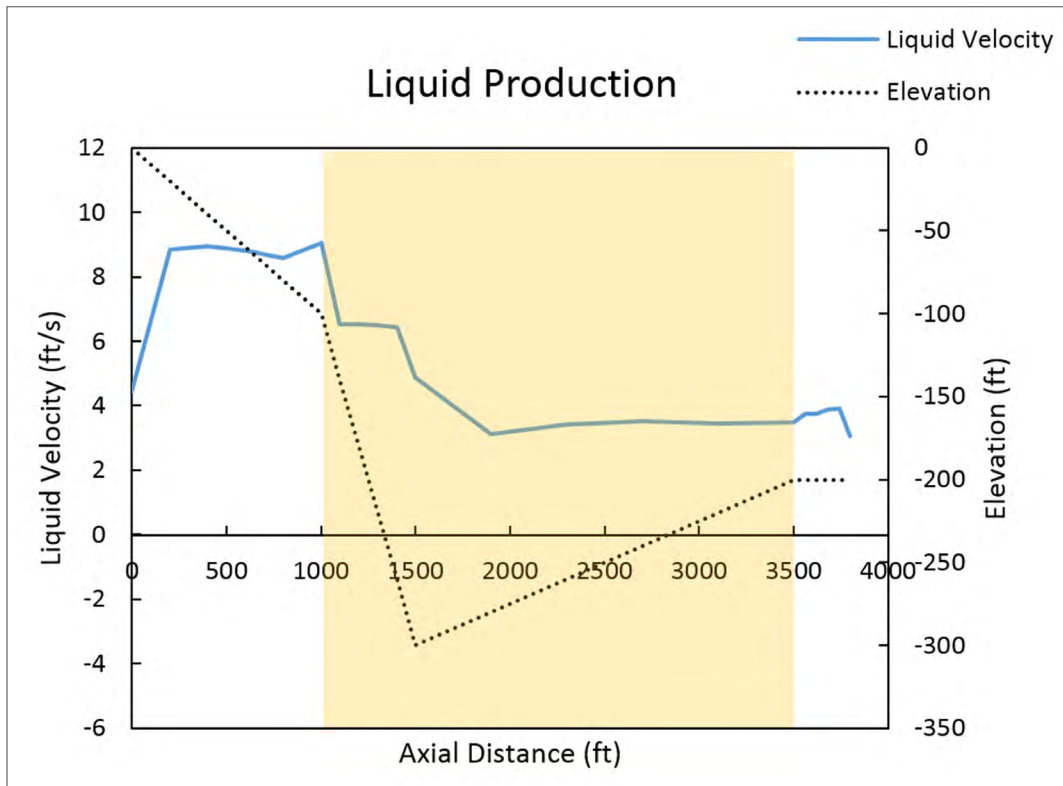


Figure 13. Liquid velocity and elevation profiles during peak liquid production

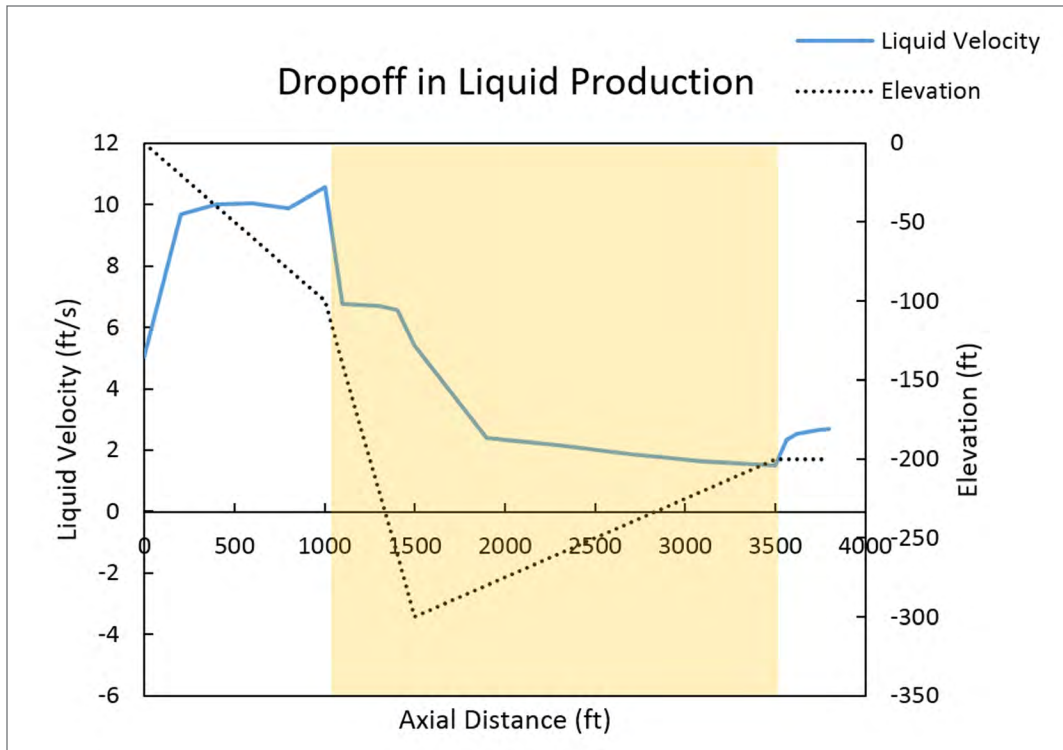


Figure 14. Liquid velocity and elevation profiles after liquid production has begun to decrease

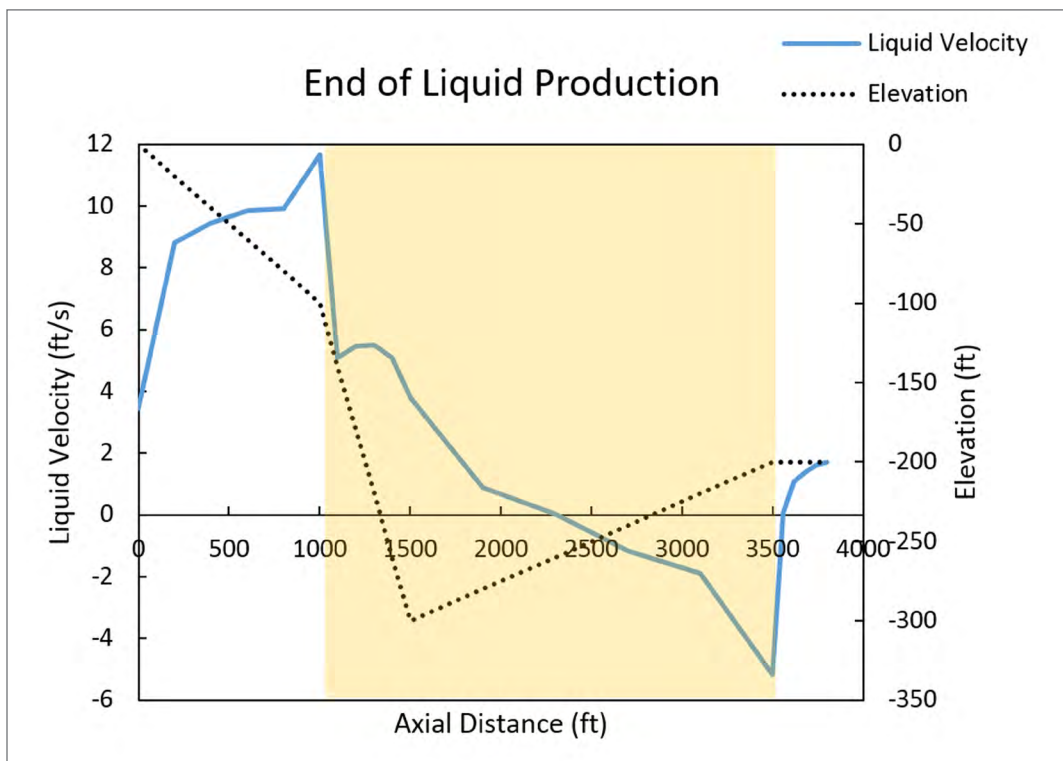


Figure 15. Liquid velocity and elevation profiles after liquid production has ended

In Conclusion

Accurate predictions for terrain-induced slugging using Aspen Hydraulics within Aspen HYSYS Upstream can enable more confident decision-making and open opportunities for capital and operating cost savings. With Aspen Hydraulics, the user can successfully model and perform transient studies of the terrain-induced slugging effect. Further, Aspen Hydraulics allows for a seamless transition for simulation in both steady-state and dynamics, as well as the seamless integration with production and processing facilities. Aspen Hydraulics also offers the ability to perform various flow assurance studies in the steady-state mode.

By fully utilizing the capabilities in Aspen Hydraulics, users in the oil and gas industry can model pipeline networks easily and accurately within Aspen HYSYS. Using information from Aspen HYSYS models, customers can avoid flow assurance issues, prevent production losses and debottleneck pipeline networks, allowing them to improve yields and increase the operability of the pipeline.

Supporting Aspen HYSYS files are available on the [AspenTech Support Website](#) by searching for the title “White Paper and Demo Files: Predict and monitor terrain-induced slugging in the pipeline.”

References

- ¹ API RP 17A. (2006, print. 2011, reaffirmed). Design and Operation of Subsea Production Systems: General Requirements and Recommendations. Fourth ed. Washington, D.C.: *American Petroleum Institute*.
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- ⁵ Sarraf, Ahad. Pipeline Engineering Studies Using Dynamic Simulation. [Process Ecology Resources](#).

Appendix

c_i	Interfacial-shear coefficient
c_{wg}	Wall-shear coefficient in the gas
c_{wl}	Wall-shear coefficient in the liquid
e_g	Specific internal energy of gas phase
e_l	Specific internal energy of liquid phase
\vec{g}	Vector of acceleration due to gravity
h_{sg}	Saturation enthalpy of gas (if vaporizing) or specific enthalpy of bulk gas phase (if condensing)
p	Pressure
q_{ig}	Interfacial heat transfer to the gas
q_{wl}	Heat transfer rate from wall to liquid phase per unit volume
q_{wg}	Heat transfer rate from wall to gas phase per unit volume
t	Time
\vec{V}_g	Gas phase velocity vector
\vec{V}_l	Liquid phase velocity vector
α	Gas volume fraction
Γ	New volumetric vapor-production rate caused by phase change
Γ^+	Maximum of Γ and 0
Γ^-	Minimum of Γ and 0
ρ_g	Gas density
ρ_l	Liquid density

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