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ABSTRACT

In an attempt simulate the hydraulic conditions actually exhibited in a pipeline, several simplifications have traditionally been made to reduce the computational requirements and complexity of the simulation models.

Recent advances in computer technology and solution techniques have allowed many of these simplifications to be removed. This paper discusses the benefit of the proper simulation of several of these areas, Transient vs. Steady state simulation, Two-phase vs. Single-phase simulation, Newtonian vs. Non-Newtonian fluid flow, Multi-component boiling and condensation in wet gas.

The effects of these features on leak detection, line pack, pressure loss, and inventory analysis are discussed, as well as the effects on pipeline design, operator training, and real time decision support.

INTRODUCTION

The art and science of computer modeling has developed into several different schools of thought regarding the purpose, application, platform, and environment which will best showcase the benefits of the model. Different industries have required dramatically different solutions to satisfy the needs for computed results.

The Oil & Gas industry has undergone one of the most interesting evolution’s in computer modeling technology and approach. The evolution has been driven by four primary industry segments, and three completely different applications. The industry segments are gas transmission pipelines, gas distribution pipelines, crude pipelines, and refined products pipelines. Some may wish to condense this list into simply transmission and distribution or gas and liquid pipelines, but this is an oversimplification of the industry. The primary applications of computer modeling can best be summarized as the on-line, off-line, and training applications.
The accuracy of the pipeline model and several of the simplifications made in the development of the models are discussed, with the purpose of identifying the limitations the simplifications place on the use of the models, and the advantage accurately modeling the hydraulic phenomena actually exhibited in the pipeline. Both ends of the simulation spectrum are explored, the desire to accurately model transient behavior compared against the pragmatic approach of simplification. The application of the model is the key determinant as to the validity of employing simplifications or accurately modeling the transients.

PIPELINE INDUSTRY
To properly evaluate the application of a pipeline model, the individual industry segments must first be discussed with attention paid to the primary needs of the segment, and the simplifications used to.

Liquid vs. Gas
One of the most obvious delineations in the industry is that of the product phase. A liquid pipeline, regardless of the type of product being moved, requires different results and has different needs than a gas pipeline.

In the event of a pipeline rupture, gas pipelines simply vent to the atmosphere, at times resulting in catastrophic explosions, while liquids spill product onto the ground and require massive clean up efforts. Inventory management is completely different as well, a liquid is essentially incompressible allowing the assumption of evenly distributed density and consistency in delivery capacity, while a gas pipeline experiences significant problems due to compressibility. The need to manage the line pack due to changes in product density in the gas pipeline is a significant problem. The effect of hydraulic surge, "water hammer", on a liquid pipeline is an important design and operational concern, while it has a negligible effect on a gas pipeline. The effect of terrain on the pipeline model is significant for liquids and is essentially dismissed by gas pipelines.

Transmission vs. Distribution
Another delineation in the industry is between the transmission and distribution pipelines. Transmission pipelines are characterized by long sections of pipe periodically interrupted by pump or compressor stations. They are traditionally well monitored, any product entering or leaving the system is measured making them prime candidates for on-line modeling. Distribution pipelines on the other hand are usually contorted and interconnected piping systems that are not as well monitored. All of the product that leaves the system is measured, but the measurements for a majority of the customers are monthly readings at meters, and the values are manually entered into the company data base. For the distribution pipeline industry, on-line modeling is not practical, too many unknowns are present, or at least the data is not available for anything other than daily or monthly readings. Simulation for a distribution network is required to be very flexible, because the number of services or customers is in continual flux.

Industry Segments
The best way to look at the pipeline industry is to look at its major components. There are subsections such as truck or tanker terminals, tank farms, collection centers, etc. that make up a small percentage of the simulation demand that will not be discussed here, rather the primary components that drive pipeline simulation are addressed.

Gas Transmission Pipelines. Gas transmission pipelines are generally considered to be the cross country movers of sweet dry gas, this discussion will also consider the transmission of sour and wet gas, usually from off-shore platforms through undersea pipeline. The movement of natural gas is an activity that benefits from the use of pipeline modeling. Several applications assist the operators in the scheduling and operation of the pipeline. The on-line model provides active data along the length of the pipeline regarding density, composition, pressure, flow rates, etc. Operators can see the condition at any point along the pipeline without having to add additional measurement devices. The look-ahead capability allows the operator to view the condition in the pipeline as it will be in the near future. The ability to move forward in time to predict pipeline conditions allow operators to guarantee that contracted delivery pressures and flows will be met, or take preemptive corrective action to the pipeline it they are not predicted to be met. The compressibility of the gas means that as compressors are rolled up or down, local changes in density occur requiring scheduling of the movement to ensure that the inventory will arrive at the required location at the desired time. This suggests that a transient model should be used to correctly simulate the dynamic effects of operation. The compressibility of the fluid means that the hydraulic surge effect is not required. The look-ahead feature suggests that a fast time capability be provided.

Gas Distribution Pipelines. Distribution pipelines take their supply from the transmission pipelines and deliver it to the ultimate users of the fuel; homes, schools, businesses, factories, etc.. The nature of the customers makes it so that continual monitoring of consumption is not cost effective, traditionally only the larger consumers have electronic measurements fed into the SCADA control room. The inconsistency in measurement makes on-line monitoring of the entire network impossible, it is limited to only those sections of pipeline which are completely bounded by active measurement devices. The primary purpose of modeling in this case is in an off-line mode, by the engineering department, who need to know the impact of adding an individual service, a subdivision, or factory on the system. With the number of different customers, the amount of data that needs to be input into the model is tremendous, generally a dump of the monthly meter readings will provide the profile for consumption across the entire network and then the individual proposed changes can be addressed. This type of modeling does not require a transient model, the endpoint is required, not the path to get there.
Crude Oil Pipelines. Crude oil pipelines require the most difficult modeling capabilities. The crude being transported frequently comes from a combination of producers with different quality crudes. Many times the pipelines are thermally wrapped to heat the crude to reduce viscosity and to prevent waxing of the pipeline due to high paraffin content. Elevation is extremely important, as is the hydraulic surge effect in the operation and modeling of the pipeline. Many crude pipelines are injecting additives such as Drag Reducing Agents, DRA, to reduce the pumping costs. The polymeric nature of the DRA leaves it susceptible to degradation due to passing through valves, pump impellers, or turbulence in the pipeline. The high cost of DRA requires that the additive be tracked by the model to allow the most efficient use of pumping energy or DRA. Leak detection and location is one of the premier uses of pipeline modeling in the crude pipeline industry. On-line transient pipeline simulation, capable of performing hydraulic surge analysis and leak detection and location are required elements of the pipeline model.

Refined Products pipelines. Many of the requirements for the crude pipeline hold true for the refined products pipeline. Elevation, hydraulic surge, leak detection and location, DRA injection and degradation are all key components of the modeling requirements. The products pipelines add another dimension to the model however, that of batch tracking. The regular scheduling of batches of different products through the pipelines traditionally require pipeline operators to spend a significant portion of their time calculating the position and anticipated arrival time of the batch fronts. This is required to guarantee that the batches are diverted into the proper storage tank at the appropriate time with a minimum of contamination. Placing batches of different products into the pipeline guarantees that there will be an interface area in between the two products that is contaminated. This region of contaminated product is affected by residence time in the pipeline, mixture do to impellers, partially closed valves, and fully developed turbulent flow. The ability of the model to estimate the size of the interface, as well as the arrival times are essential additions to the model.

Multi-Phase Pipelines

Most pipelines have been simplified to be represented as single phase gas pipelines or single phase liquid pipelines, reality however is not so simple. A great many gas pipelines, particularly those coming from both on-shore and off-shore wells have a distribution of hydrocarbons ranging from Methane all the way down to Decane. In these wet gas pipelines, the heavier hydrocarbons will condense. The condensation of gases into liquids has a significant impact on the hydraulic operation of the pipeline. As gases condense the liquid component takes upon significantly less volume, decreasing the density or line pack of the gas phase, at the same time decreasing the average specific gravity and increasing the concentration of the light hydrocarbons. This cross sectional area of the pipe is decreased as liquid accumulates in the pipe bottom, leading to the possibility of blockage of the pipe in low lying sections of the pipeline, causing a slugging event to occur. If the pipeline is depressurized due to drafting, loss of compression, or a leak the condensate will then boil or flash. With wet gas these events occur in a step pattern as the saturation conditions for each successive hydrocarbon is reached. The flashing of the condensate suddenly increases the specific gravity and concentration in the pipeline, inventory, velocity, density, composition, temperature, etc. are all affected.

Condensate pipelines that are liquid only due to pressurization, or crude pipelines that run through mountainous terrain exhibit the opposite problem from the wet gas pipelines. Liquids frequently flash in pipelines, an event referred to as “slack line”. The slack line phenomena introduces a large volume of gas in the pipeline, this transient causes more liquid to leave a region than enters it as the volume of gas increases, conversely as the gas volume is recollapsed more liquid enters the region than leaves it, which is the classic profile of a pipeline leak. This set of events play havoc with leak detection and location or batch tracking systems which are based upon single phase technology.

The modeling of a multi-phase pipeline requires that a full energy balance be maintained in the pipeline, that the thermodynamic properties if each component be maintained, and that the model be capable of performing the individual boiling or condensation of each of the individual components.

COMPUTER TECHNOLOGY

In the evolution of pipeline modeling, the capability of the computer and the operating system has been an important factor. As late as the early nineties, the computing resources necessary to perform detailed transient analysis were cost prohibitive. As a result, simplifications or concessions were made in the models and in the solution techniques. One of the major concessions includes the simplification of thermal equilibrium and the subsequent removal of the energy balance. This simplification has led to the implementation of separate models used for liquid and gas pipelines, leading to inherent limitations in the model when applied to pipelines that experience two phase operation.

Presently in the pipeline industry there are several different pipeline modeling vendors and several different SCADA vendors. Almost every SCADA upgrade or replacement contract that is let includes a request for pipeline modeling, either on-line, off-line, training simulation, or leak detection. This has traditionally meant that a SCADA vendor with one operating environment, graphics system, and alarm system has to pass data to a separate simulation model with its own operating environment, graphics system, and alarm system. The question as to what environment the model will be based upon is therefore a two-pronged question, the computer platform and operating system, and the operator interface.

The industry is moving in a definite direction, that is to smaller, cheaper, faster, more standard computers running the next generation standard operating system. This is the Intel® based Pentium® computer running the Windows NT® operating system. Pipeline companies have with greater frequency, been specifying that the operating system for a SCADA system upgrade, or for a pipeline model be in the Windows NT® environment. Pipeline modeling and SCADA vendors have recognized this trend, because of the cost of converting their systems, and the attitude of their senior management, some of these companies have proactively embraced the technology.
The use of a steady state model to run successive calculations is not a satisfactory solution to transient simulation. Multiple runs of a steady state model give discrete solutions for the pipeline at given points in time, these individual solutions give a result that is valid for that unique condition but that is completely unrelated to the solution that occurred before and after it. This means that in a transient event on the pipeline, a valid solution can be delivered, the pipeline can undergo a change in conditions, even violating operating conditions, then another solution can be made by the steady state model which will appear to be a valid solution but is not connected to the previous solution, and indication of operating condition violations are never identified. A steady state model is not capable to calculate these pipeline events but the transient model is.

ACCURATE PIPELINE REPRESENTATION

The first and foremost purpose of the pipeline model is to accurately represent the conditions within the pipeline itself. This means essentially that the pipeline model’s job is primarily to give back to the operator exactly what is being measured in the pipeline anyway. This may sound simplistic, but until a pipeline model can perform this most basic function, no other application can be relied upon, including the most important application of leak detection.

Every pipeline experiences transient conditions, changes in load, changes in pressures, flows, number of compressors, etc. A great many pipeline systems experience phenomena related to changes in phase as well, this includes liquid pipelines which experience “slack line” conditions or flashing in the pipeline, and wet gas pipelines which experience condensation in the pipeline system. The majority of pipeline models are by definition, single phase models and are incapable of properly representing these cases. When a pipeline enters a two-phase region, the density, composition, velocity, and pressure loss profile change. In order to properly perform leak detection, the simplistic comment is again stated, the first and foremost purpose of the pipeline model is to accurately represent the conditions within the pipeline itself. If the model is incapable of this function, then the leak detection and all other applications are suspect, or must be turned off during these conditions.

SimSuite Pipeline™, which is used as a reference for this paper, is a six equation model, providing a complete mass, momentum, and energy balance for both the gas and liquid phases. The ability of the SimSuite Pipeline model to accurately represent the worst transient condition of real time boiling and condensing of components based upon the thermodynamic conditions within the pipeline means that the model is able to be very accurate when analyzing the transient operation of the pipeline and therefore properly representing the pipeline conditions.

Simplifications

Simplifications are made in order to reduce the mathematical complexity and decrease calculation time. As computers get faster and configuration tools get better, many of these simplifications can be reduced or removed.

The simplification regarding thermal calculations is a prime example. In the past many different simplifications have been suggested and used, from dismissing the energy balance altogether, to assuming a fixed temperature profile, to complete simulation of the energy solution including the heat transfer. Under the correct
conditions each of these simplifications can be justified, they are not justified for operational transients or for all pipelines. With the computing power available and the low prices now available, the computer time required to perform a complete energy solution is not significant enough to justify continuing to make these simplifications.

Other simplifications include the time step used for transient calculations and the nodalization of the pipeline. The real world is a continuous (analog) process. Time is continuous and the properties in the pipeline change uniformly. Today's digital computers require the pipeline model to be broken into discrete segments for calculations, both in time and space. The granularity of those steps has a large impact on the accuracy of the results. In the past, time steps were very large, several seconds or even minutes. Today's standards have fallen to multiple solutions per second and will continue to decrease. The pipeline must also be divided into discrete volumes. For each of the volumes segments the mass, momentum, and energy conservation equations are applied.

The methodology for nodalization of the pipeline can be identified in two different areas, the pumping/compressor stations and the remainder of the pipeline. The stations can be simplified to ignore all of the internal flow paths within the station. This can be justified for simplified on-line models were the station exit pressure and flows can be obtained from SCADA data. The other alternative is to completely simulate all flow path, individual pumps, valves, tanks, strainers, heat exchangers, etc. The drawback is the time required to configure the model. This is possible with good graphical configuration tools and sophisticated computer models. Accurately simulating the complete dynamics of the station is very important for training stations and off-line dynamic analysis. The nodalization of the pipeline is limited only by the computer power. Typical maximum length for calculation volumes in the pipeline is 500 to 1000 ft.

The simulation of the pipeline logic and control has also been greatly simplified in pipeline modeling industry. As the importance of training simulation and off-line transient analysis increase, these simplifications will have to be changed. The biggest limitation to logic simulation is the man-hours/cost to configure the control and logic model. In order to minimize the man-hours it is important to have a graphical user interface allowing the configuration of the logic model, with the ability to import logic and control information directly from the actual pipeline data. The inclusion of the logic and control simulation into the transient analysis provided the foundation for a training simulation system that will be compliant with the operator qualification guidelines from the Department of Transportation - Office of Pipeline Safety.

Solutions Technique

The mathematical solution used in transient pipeline simulation falls generally into two separate approaches, Method of Characteristics and implicit matrix solution. These two separate techniques are simply that, different techniques. These techniques both provide valid numerical solutions to the pipeline structure, but take a significantly different approach. Depending upon the desired application each has its advantages over the other, but the differences need to be discussed.

Implicit solutions are extremely good a providing solutions for complicated piping networks, and allow very good fast time analysis, which is important for look-ahead and off-line engineering analysis, but it tends to wash out or distribute the effects of hydraulic surge. The Method of Characteristics solution is very good a modeling the effects of hydraulic surge, but is very poor at complicated piping networks and is very limited in the fast time functions that can be performed.

Method of Characteristics. The Method of Characteristics solution technique is well established, and is the only solution approach to a hydraulic network which can accurately represent the effect of the hydraulic surge. The ability of the model to calculate the surge pressure as it travels the distance of a pipeline at the speed of sound comes with limitations to the use of the solution. The technique sets the length of the segment as a function of the time step such that fast time calculations used in the look-ahead analysis are limited to the spare time of the computer and the CPU speed. The approach is also limited to relatively uncomplicated pipe structures, transmission sections of pipe are perfectly suited to this method, but the complex architecture of the pump station or a distribution network are not.

Implicit Solution. The implicit solution solves the total pipeline matrix simultaneously, this method is perfectly suited to the complex structures of pump stations or distribution networks. In addition, the time step in not physically linked to the volume of the matrix or pipeline section. This has the advantage of allowing the time step to be adjusted, allowing fast time analysis to be performed in the transient simulation. A major drawback to this approach is that because the entire matrix is solved simultaneously it is incapable of calculating the surge wave as it travels through the pipeline. The pressure surge tends to be “washed out” or distributed through out the network.

Both the Method of Characteristics and the Implicit solution are valid numerical solutions. They both arrive at the same endpoint pressures and flows, however, they take different paths to that solution providing unique benefits and drawbacks along the way. GSE Systems has attempted to provided the best of each feature to the solution of a pipeline network. SimSuite Pipeline provides a unique capability to the pipeline modeling world. This is the ability of the model to provide either an implicit matrix solution or a method of characteristics solution, or a combination of both in the same network depending upon the requirements of the customer and the pipeline.

Transient Pipeline Conditions

The real world application of the pipeline system is generally not a simplified system. The representation of the steady state solution, with a single phase simplification, with no energy balance does not represent the pipeline. Recall the original premise of pipeline modeling, “The first and foremost purpose of the pipeline model is to accurately represent the conditions within the pipeline itself." The following topics emphasize some of the primary transient concerns;
SimSuite Pipeline is a multi-component system which provides the ability maintain the composition of each individual hydrocarbon in both the gas and liquid phases. When chromatography data provides the composition of the gas, including non-condensible gases, water, and hydrocarbons, the simulation model maintains a complete mass and energy balance of each component in both phases. The proper thermodynamic effects are simulated in the pipeline so that as the saturation conditions are reached for each component, they will successively boil or condense as required. Simulation of this phenomena is a particular strength of the SimSuite Pipeline simulation model.

Newton vs. Non-Newtonian Characterization. With the simulation of liquid hydrocarbon pipelines, the ability to represent the viscosity becomes extremely important. The fact that hydrocarbons are not Newtonian fluids means that the simulation model needs to be able to represent a non-Newtonian characterization. Newtonian fluids have a linear response to shear while non-Newtonian fluids generally have a non-linear response to shear, and may exhibit a yield stress allowing the fluid to gel during shut down conditions.

During fully developed turbulent flow the operating region of the non-Newtonian fluid may be accurately approximated with the Newtonian model by assigning an effective viscosity for the region where the two curves intersect, however this does not change the fact that the fluid is non-Newtonian, and as the pipeline operating conditions change from this region, the response to shear will diverge from the Newtonian approximation.

Additives. Many pipelines use additives such as Drag Reducing Agents (DRA) to improve their delivery capability and to reduce the cost of pressurization. To accurately represent these pipelines, the simulation model must include DRA algorithms to modify the normal pressure loss characteristics of the physical pipeline. This capability must include DRA degradation through check valves, valves, pumps, and the pipeline itself. The effects of DRA are model by reducing the admittance based on the concentration of DRA in the pipeline. The transportation of the DRA through the pipeline is the same as any other species with the important difference that DRA reduces the pressure drop per length of pipeline, and it is degraded as it is transported through the pipeline.

The reduction in pressure drop is very specific to the DRA used and the pipeline product being transported. The values of each of the parameters in the equation need to be obtained by working with the individual customer.

The effectiveness of the DRA is calculated based on the following empirical formula.

\[
\frac{1}{Eff_{DRA}} = A + \frac{B}{PPM} + \frac{C}{PPM^2}
\] (1)

The effectiveness constants A, B, and C are specific to the DRA type and product into which it is injected. The DRA effectiveness is used to modify the friction factor. The friction factor may be calculated from various correlation's such as Fanning, Darcy-Weisback, etc.
\[ f_{DRA} = f \times E_{DRA} \quad (2) \]

DRA is degraded in the pipeline proportional to the local shear stress. This causes a small degradation in the pipes, and larger degradation at each of the pumps and/or valves in the line. The effective degradation of the DRA is unique for each pump or valve type traversed, and the ability to specify the degradation for each individual pump, check valve, valve and slack line event is essential.

Local Gas Distribution pipelines and Gas Transmission pipelines are required to inject odorant as an additive to the pipeline system for safety purposes. While odorant does not modify the pressure loss profile like DRA, it does dissipate in the pipeline over time, and the ability to track the composition of odorant with its attendant losses is a benefit to pipeline operations.

**MODELING APPLICATIONS**

The accurate representation of the pipeline with the simulation model has a significant impact on the higher level applications provided by pipeline modeling. The following discussion includes some of the impact of simplifications each of these applications;

**Leak detection and location**

The complete modeling of the energy balance in the model is extremely important in the leak detection and location application. Simulation models that are single phase only must be placed out of service when two phase conditions exist. Pipelines that exhibit two phase phenomena whether they are liquid pipelines in slack line or gas pipelines with condensation still require leak detection functionality. When a slack line condition exists the imbalance of incoming and exiting flows provide a condition in the leak detection model where there is a magnitude of error that the leak thresholds have to be widened so much that the model is invalid, unless the pipeline model understands and accurately represents the slack line condition. The ability to model the two phase condition allows pipelines that operate in two phase conditions to have and operations leak detection model.

**Line pack/draft**

One of the primary functions that a simulation model provides to a gas pipeline is the inventory tracking for line pack and draft applications. The ability to track the individual hydrocarbons (C1, C2, C3, ...) allows accurate volume, mass, and energy pack to be determined. The introduction of condensation into the pipeline dramatically changes the composition, line pack, energy pack, density, velocity, and pressure loss profile. The ability of the model to simulate the condensation allows it to provide the correct line pack and inventory analysis.

**Operator qualification and training**

One of the benefits of pipeline modeling is that it allows the opportunity for operator training to be performed. The fundamental purpose of operator training is to provide positive and effective training, a model which incorrectly represents the conditions of the pipeline provides negative training which in some cases is worse than no training at all. A training program allows the stress associated with upset events in the pipeline, including simulated leaks, to be managed. Operators have the opportunity to experience and respond to these conditions repetitively and become competent in the response, incorrect response of the simulation model teaches and incorrect response to an incorrect event.

The Department of Transportation - Office of Pipeline Safety issued a proposed rule in 1994 stipulating a level of operator training and certification that would rival the training programs required for nuclear power plant operators. This level of training was objected to by the pipeline industries, and a negotiated ruling containing a compromise operator qualification guideline was being released in April, 1998, it will become effective in August, 1998 and within three (3) years, each pipeline system must be compliant with it. Operator training simulators have been reviewed by the Office of Pipeline Safety and have identified as a tool which provides a training and qualification program that is completely compliant with the new guidelines.

**Pressure loss**

The introduction of DRA into a pipeline, the representation of non-Newtonian characterization, and the correct analysis of two phase flow have a tremendous impact on the pressure loss or hydraulic profile. DRA changes the slope of the profile from the point of injection as the pressure loss is decreases.

A slack line event keeps the pressure in the pipeline at the saturation conditions of the pipeline. This means that as the gas bubble increases in size, the pressure profile actually follows the terrain of the mountainside until the pipeline is solid, at which point it will follow the normal pressure loss profile. A two-phase model will correctly represent this condition, while a single phase model will represent a profile which "tunnels" through the mountain, which is a physical impossibility.

Either of these two events, the change in pressure profile due to DRA or the slack line event invalidate the leak detection system.

**CONCLUSION**

Pipeline simulation is an extremely beneficial feature for pipeline operation, the high level applications that it provides allow the pipeline to be operated more efficiently and safely. Critical to these applications however, is the reliable and accurate representation of the pipeline conditions.

Pipelines that exhibit purely single phase conditions and have used steady state results have been fairly well represented by the pipeline modeling industry because the pipelines conform to the simplifications of the models. The industry segments which exhibit condensation and slack line conditions and that have needed the transient response have not been well served. The inclusion of the full energy balance, allowing accurate representation of the pipeline in all of its operational ranges and conditions provides the opportunity to have these applications accurately provided.

Accurate on-line transient simulation, with the inclusion of complete energy balance modeling for the pipeline are features in the
modeling of pipeline systems that should no longer be considered as high end applications that are not suitable for the general pipeline population, but instead should now be expected as the standard for pipeline modeling. Pipeline companies should expect this from the pipeline model vendors as a mechanism to safely and efficiently operate the pipeline system.