

***Transient and Succession-of-Steady-States
Pipeline Flow Models***

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INTRODUCTION

Pipeline operations are inherently transient processes. Inlet and outlet flows change, pumps and compressors start and stop, control setpoints change, different products and compositions move down the line, and temperatures change with changing ambient conditions. These facts would seem to indicate that a useful pipeline flow model should be a transient model, that is, it should solve the time-dependent flow equations. However, steady-state models are widely used to design pipelines, and to estimate the flow and line pack. Succession-of-steady-states (SSS) solutions corresponding to sequences of boundary conditions, control setpoints, equipment statuses, and interface positions are used for tracking or estimating the movement of products through pipelines. This paper addresses the two types of models and their suitability for various purposes.

PURPOSES OF PIPELINE FLOW MODELS

The appropriateness of a particular type of flow model depends on the use to be made of the model results. Pipeline flow models are used for the following purposes:

Product Tracking - Batches of different products, composition, quality, cost, origin, and ownership can be tracked through a pipeline. The objective for offline product tracking models is usually to estimate schedules. For real-time models the objective is usually to estimate interface arrival times. Product tracking may also be used to estimate allocations of ownership and specific (as opposed to average) transmission costs. For both real-time and offline models knowledge of interface locations is necessary for accurate hydraulic calculations.

Line Balance - The net flow in and out of the pipeline, by batch or over time intervals, is a check on the integrity of the pipeline and/or the metering process. A flow model permits the calculation of more accurate line balances by estimating the change in line pack

Line Pack Distribution - Flow models are used to estimate the distribution of product in the pipeline as an aid to managing the product inventory temporarily stored in the pipeline.

Pressure Monitoring - Flow models provide estimates of the maximum/minimum

pressures at points between pressure sensors.

Deliverability - The maximum achievable delivery flow rates at specified points can be estimated with flow models.

Pump/Compressor Performance Monitoring - By comparing model estimates of current performance with manufacturer's specifications, changes in the performance of pump or compressor stations and individual units can be detected.

FUNDAMENTAL DIFFERENCES BETWEEN TRANSIENT AND SSS MODELS

The underlying difference between transient and steady state models lies in the equations of motion. The transient equations contain terms for the rates of change with time of the dynamic variables: pressure, temperature, density, and velocity. By setting these rates of change equal to zero, which is the mathematical expression of the steady-state condition, the steady-state equations of motion are obtained. However, in considering the suitability of transient vs. SSS for various purposes, differences in the results are of more interest than differences in the equations.

The results of the two approaches have in common the production of spatial arrays of the dynamic variables at successive points in time. The values in these arrays are not generally the same for the two types of models. The transient values are the result of changes in the dynamic variables caused by the transient flow processes since the previous time step. The SSS values do not depend on the previous values, except insofar as the external boundary values depend on the previous step. The SSS solution process results in arrays of values that are consistent with the current boundary conditions and the steady-state assumption. Each successive steady-state solution is, in principle, independent of what went on before. (Aspects of the pipeline operation that are treated separately from the hydraulic model, such as batch interface movement, are of course not independent of previous steps in either transient or SSS models.) Models based on the SSS approximation are often much easier to implement than full transient models; steady-state solutions are not subject to a menagerie of numerical instabilities that transient models must avoid. This is not to imply that transient models are necessarily fragile, just more difficult to implement robustly.

Since many applications are interested in changes over time, the means and accuracy for obtaining the magnitudes of these changes from the model results are important considerations. Such changes are intrinsic to the transient solution; the rates of change of the dynamic variables are obtained straightforwardly by plugging the current values of these variables back into the equations of motion, which then become expressions for the rates of change. Obtaining estimates of the rates of change from SSS results is also straightforward: the rates of change are estimated as the difference between the current values and the previous values, divided by the time interval. The issue is the accuracy of these estimates.

STEADY FLOW

A very significant difference in the results is that the flow (measured as a standard volumetric flow) in a steady-state model must be the same everywhere along any linear section of pipeline which contains no injections or deliveries. Were this not so, the line pack would be changing and the model would not be steady-state. This fundamental property of steady-state solution creates obvious problems for applications requiring packing rates, since any steady-state solution has a packing rate of zero. This difficulty is dealt with by estimating the packing rate to be the difference in the line pack for two successive steady-state solutions. Again, the accuracy of this estimate is the question.

A transient solution contains variations in the flow along the pipeline. Changes in boundary conditions, setpoints, and equipment statuses create *transients* or *surges* that propagate along the pipeline. Such transients do not exist in the individual steady-state solutions, and are therefore completely unrepresented in SSS methods.

THERMAL DIFFERENCES

The steady-state thermal solution produces a temperature profile that is in equilibrium all along the pipeline. Since the temperature profile typically requires hours to reach equilibrium after a change in, e.g., the inlet temperature, the steady-state thermal solution has significant errors which persist over long periods resulting from transient pipeline operations.

The usual transient model, which is based on a finite difference solution of the energy balance equation, also has difficulties. The resulting temperature at each model point is essentially an average temperature over a distance step, applied to a point associated with the step in the solution procedure. This type of solution has numerical dispersion, in which a temperature front, such as that resulting from a change in the inlet temperature, is broadened as the front moves

down the pipeline. In reality, the front remains sharper than the solution would indicate. There is also a non-physical effect of temperature changes propagating down the pipeline much faster than the speed of the fluid, which is the actual speed at which the temperature front moves. These non-physical effects of the transient model can be made small by using small distance steps in the numerical solution. However, practical pipeline models commonly have distance steps of one mile or more, so that the numerical dispersion effects are significant. These effects can also be reduced by different numerical formulations of the transient model.

This paper will examine the significance of these thermal errors for both SSS and transient models. A third approach, using a propagating temperature front rather than an energy balance will also be discussed.

ACCURACY OF TRANSIENT AND SSS SOLUTIONS

Several times in the previous section accuracy was mentioned as being important to the applicability of the model, with the implication that accuracy is a larger problem for SSS solutions. The practical truth of this implication depends on the need for accuracy in a particular application, and on the limitation on the accuracy of both types of models due to external considerations. Both transient and SSS model results are approximations to the actual conditions in the pipeline because of imperfect knowledge of the boundary conditions, fluid properties, equipment properties, and ambient conditions. There are also inaccuracies in both types of models due to the limitations of numerical solution techniques.

The inaccuracies due to the numerical techniques arise from the fact that values of the dynamic variables are calculated at discrete points in time and space. Nearly all numerical models assume that changes in the values between these points are linear. While most pipeline models are based on the same physical equations, numerical techniques differ in the manner in which these equations are solved. Since the physical equations are not in general subject to analytical solution, these differences are in the form of approximation used. Generally, different approximations will give different results, although these results will generally converge to the same solution in the limit of short time steps and short distance steps.

Often, there are also inaccuracies because some fluid properties (such as viscosity) are assumed not to change during the time step. This assumption is made as a practical matter because the property often depends in a complex way on the density and temperature.

Some important parameters are not reasonably determinable. These parameters include the ground thermal properties (effective conductivity and undisturbed ground temperature) and, in the transition zone between laminar and turbulent flow, the turbulent state of the fluid. Offline design studies of pipelines are often done with only very approximate estimates of the flow rate and mix of products or compositions that the line will be shipping. For real-time models, measurement errors may also limit the accuracy of the model.

A great deal of work, some of it elegant and successful, has been done using feedback tuning and state estimation to minimize the effect of such errors. Notwithstanding the power of these methods, the accuracy of models is commonly limited by external sources of error, to the extent that more accurate modeling techniques may not produce more accurate results.

COMPARISON OF TRANSIENT AND SSS MODELS FOR VARIOUS PURPOSES

PRODUCT TRACKING

Whether one is tracking compositions, batches, qualities, or economic quantities such as ownership or origin, the basic technique is to use a type of "dead reckoning" over each successive time step to calculate the movement of a point. The point may be a batch interface or a point in the fluid at which the values being tracked are known.'

The accuracy of the tracking is a direct consequence of the accuracy with which the velocity of the moving point is given by the model. Batch schedule simulators are commonly required to simulate a week or a month of pipeline operation. Schedules are developed by a trial and error procedure to produce a final schedule that is reconciled with nominations, pumping power, availability of tankage, and interfaces with other pipelines. The length of the period simulated and the number of trials make speed of the essence. Whether the model is SSS or transient, large time steps, typically one hour, are required. Over such a large time step, sharp transients largely decay, which diminishes the advantage in accuracy intrinsic to transient models.

Figure 1: Batch Interface Movement

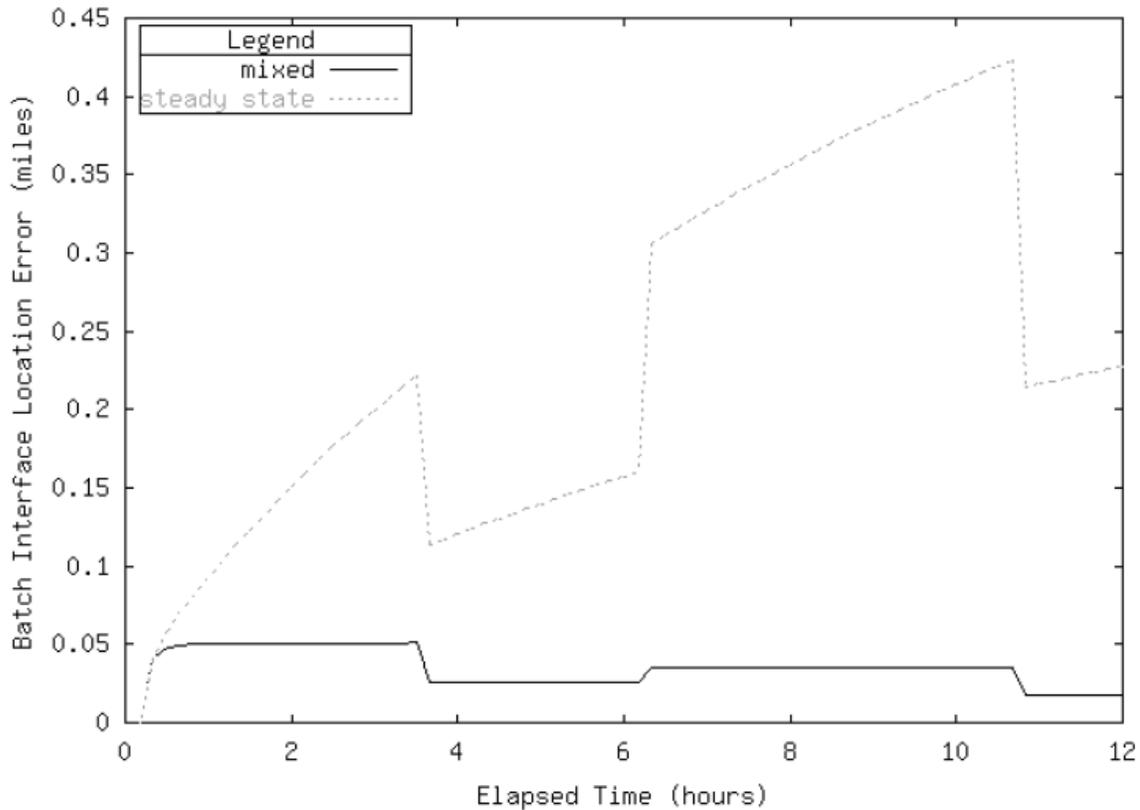


Figure 1 shows the error in the location of a batch interface for an SSS model and a "mixed" model (explained below) as compared with a transient model. This model is simulating a batch transit over a 120 mile section of pipeline with two pump stations, one of which is started 5 minutes into the simulation period. The line is pumping a heavy crude for which the viscosity drops rapidly as temperature increases; this means that errors in the temperature profile in the line translate into errors in the flow rate. The newly started pump station causes two independent transient effects: first, it causes a surge as discussed above, and second, it causes warmer crude to slowly fill the line. Although this fluid is only a few degrees above that which was previously in the line, that's enough to give it a significantly lower viscosity.

The interface position error seen here for the steady state model comes to about half of a percent over the whole length of the line. This model treats the entire pipeline as if it was instantly filled with the heated crude, and so immediately jumps to the higher flow rate. The "mixed" model is an SSS hydraulic model coupled to a transient thermal model. It can be seen in Figure 1 that the mixed model's error in the interface position is reduced to a negligible level. This model captures the dynamics of the heated fluid from the newly started pump station as it fills the

line. The remaining error common to both SSS and mixed models, which arises in the first few minutes of the simulation, is due to the unmodeled hydraulic transient associated with the pump start.

A similar run with gasoline instead of crude in the line produces errors for both the SSS and mixed models of at most 0.05 miles, less than a tenth of a percent of the distance covered. The hydraulics of the gasoline are not strongly affected by its temperature, so only the relatively small component of the error due to the failure of the steady-state hydraulics to model the transients is seen. The jumps in distance error are an effect of the batch interface passing through pipes of different diameters.

A gas planning model faces a similar situation: projections are typically for several days, and are re-run regularly as externally imposed conditions such as loads change, again requiring large time steps for the sake of model speed. However, in addition to movement, the line pack distribution is of interest. The relative accuracy of the line pack distribution will be discussed in a subsequent section.

LINE BALANCE

Line balances are used as a check on the integrity of the pipeline and/or the flow measurements. Practical applications include the best leak detection systems and flow meter cross-calibration systems. The straightforward line balance is the difference between the net flow into the pipeline (that is, the flow in minus the flow out) and the packing rate. In the absence of a leak, the quantity must be zero. In practice, the flows in and out of a section of pipe come from external sources. These may be flow meters or, if accurate measurements aren't available, model calculations for adjacent sections. The packing rate is calculated from the pressure and temperature profiles for that section of the pipeline. The pressure and temperature profiles are obtained by interpolating between measurements or from a real-time model driven by those measurements. Because measurements are typically separated by the distance between pump or compressor stations, model profiles are generally much more accurate than interpolation.

For steady flow, the SSS and transient models produce the same results. A pressure or flow change at either end, or a temperature change at the upstream end produce transients, commonly called surges, which propagate along the pipeline. The leading edges of pressure and flow surges propagate at approximately the wave speed, which is the speed of sound in the fluid reduced by the effect of pipe expansion. The peaks of these surges propagate at a somewhat slower speed, but still move very fast.

SSS models will not show the surges at all. While the surge is in the pipeline, line balances calculated from an SSS model will have significant errors. These errors can be removed by averaging over times large compared to the propagation time of the surges. Transient models simulate the surges to within the accuracy provided by the size of the time and distance steps.

Figure 2: Line Balance with Steady State Approximation

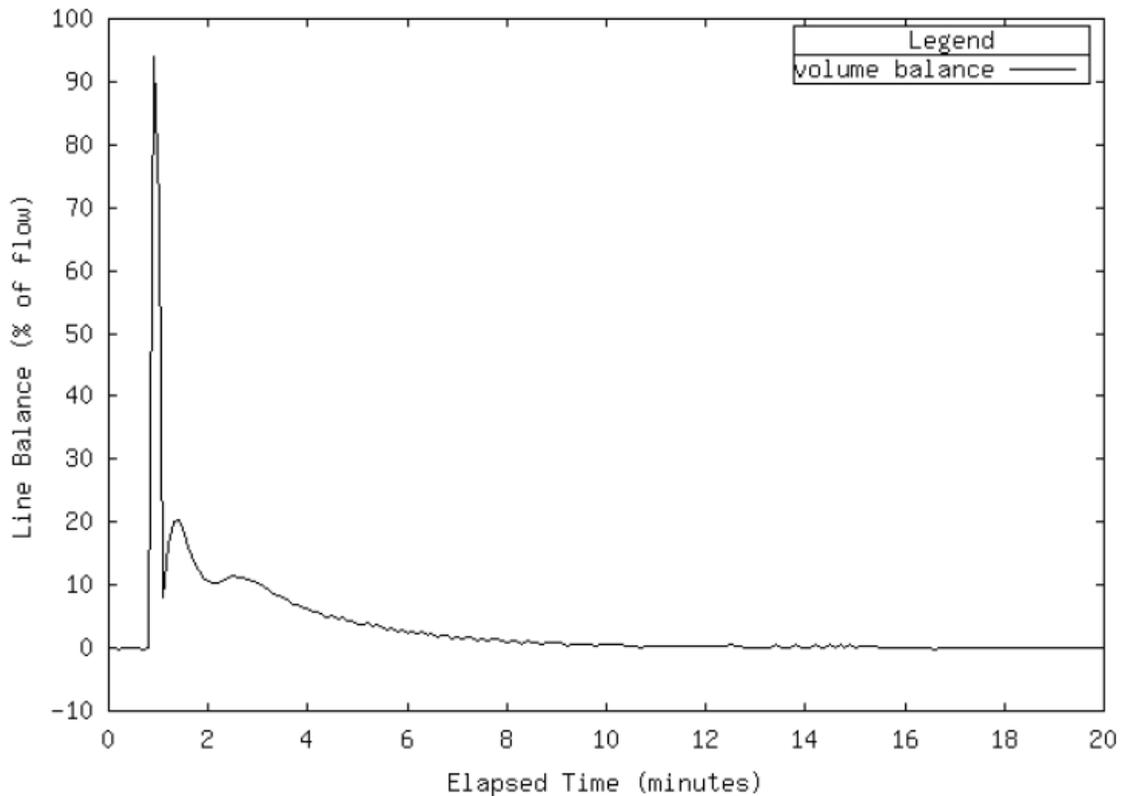


Figure 2 shows the line balance for an SSS model in ideal circumstances with surges caused by pump starts for the same two-station system that was simulated in Figure 1 (this time pumping gasoline). In these ideal circumstances (meaning that there are no pressure measurement errors and no errors in the physical configuration) the transient line balance is zero. In reality, a well-tuned transient model typically has line balances of a few percent of the flow due to measurement and configuration errors.

LINE PACK DISTRIBUTION

For large gas transmission pipelines the gas stored in the pipes is an important factor in managing

the operation. Fluctuating loads or supplies can be handled, at least in part, by unpacking or packing the pipeline. The accuracy with which the line pack and its distribution are determined by a model is a factor in determining the model's usefulness. The two major model errors producing line pack errors in an SSS model are again pressure transients and thermal transients. For typical transmission pipelines, an average pressure error of 10 psi, or a temperature error of 5 °F will produce a 1% line pack error. A compressor start will typically produce pressure surges of over 100 psi, which will decay in about one hour. The same compressor start will produce (in the absence of aftercoolers) a temperature front with a change of about 50 °F which will move down the pipeline at the gas velocity, decaying as it goes. Average temperature errors >10 °F may persist for a couple of hours.

Figure 3A: Upstream Line Pack

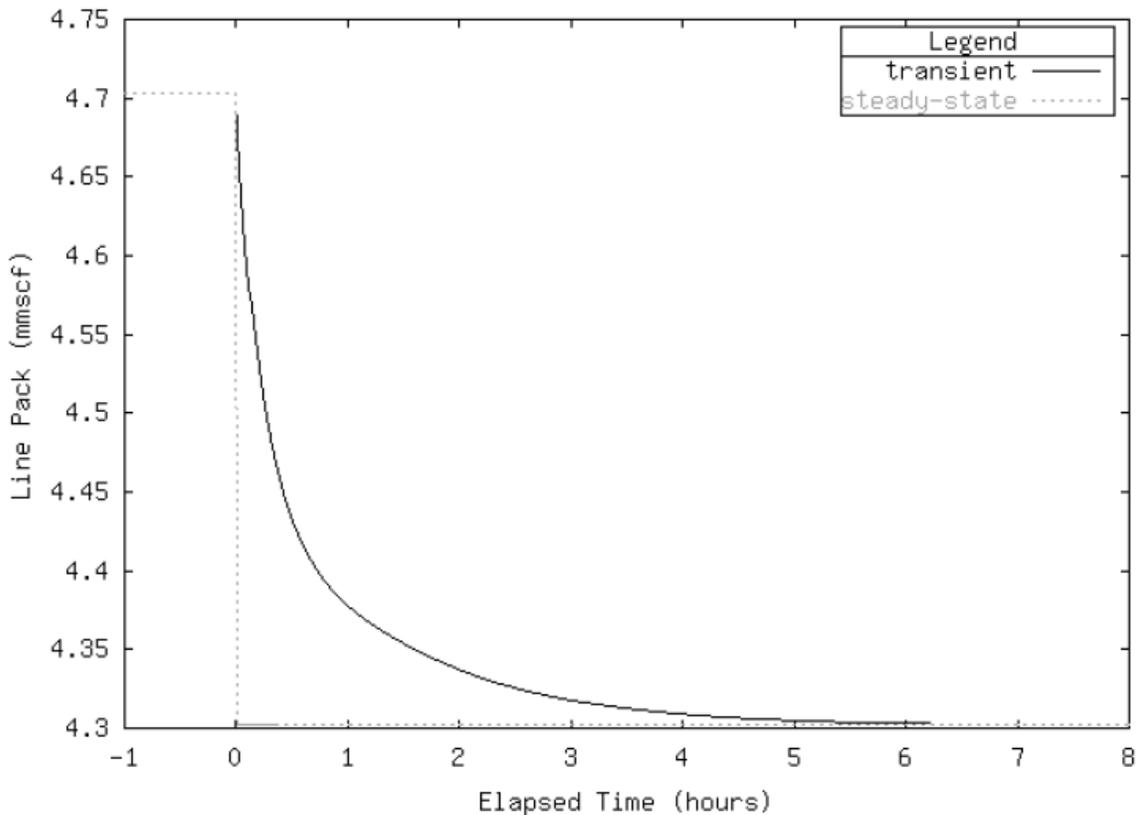
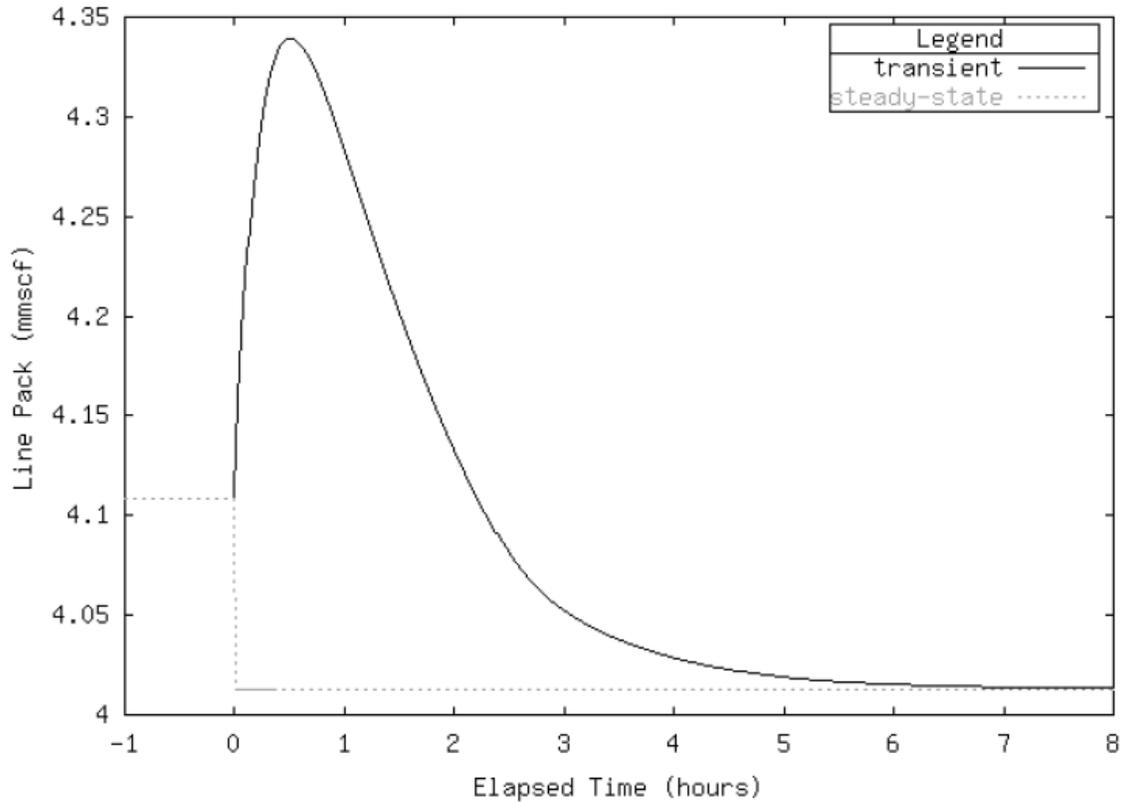


Figure 3B: Downstream Line Pack



Figures 3A and 3B show the line pack trends in the upstream and downstream sections of a 120 mile section of pipeline with a compressor station at the midpoint. The station is initially shut down, and started at zero hours. It can be seen that even an hour after the station starts up; line pack errors of 100% of the eventual change in line pack remain in the SSS model.

Figure 3C: Pressure Profile 30 Minutes After Compressor Startup

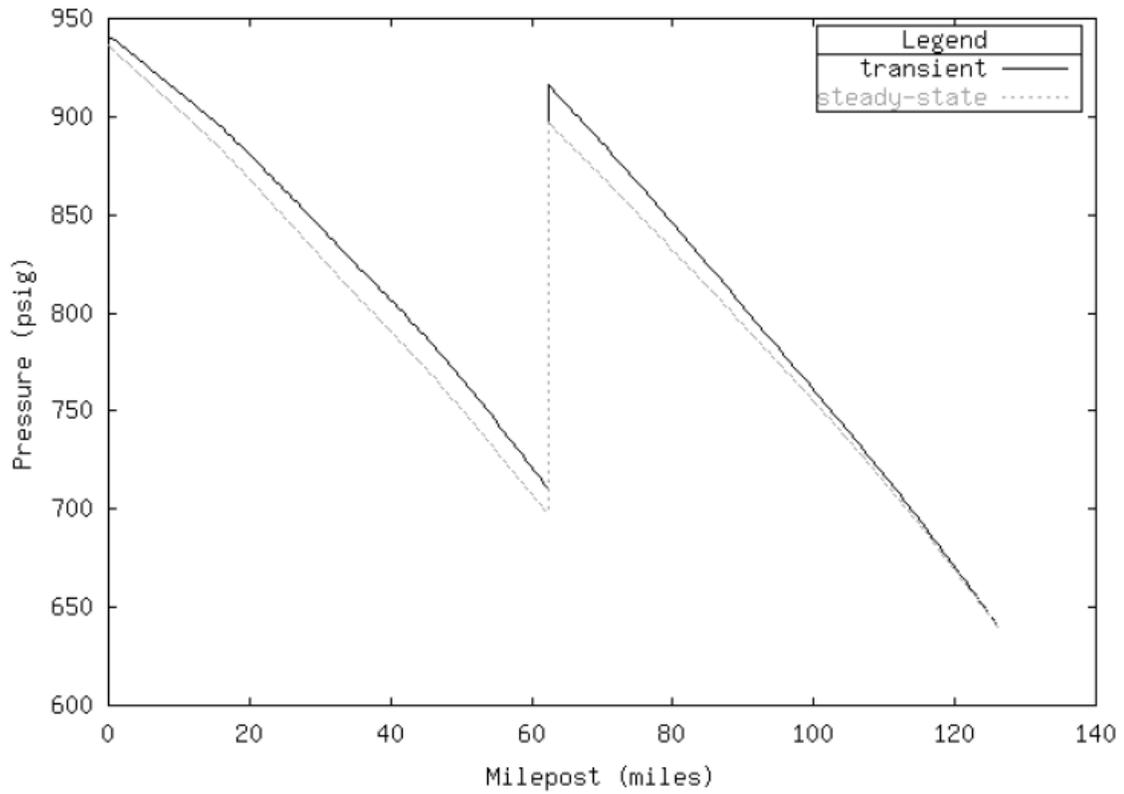
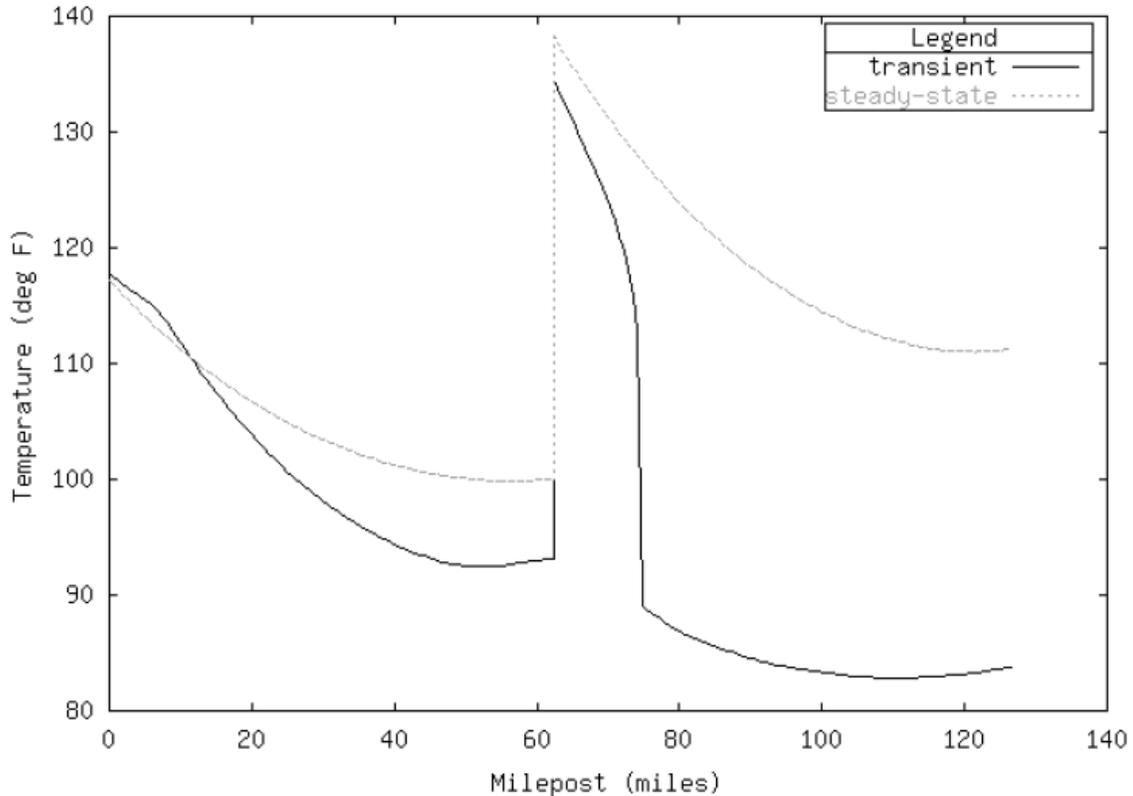


Figure 3c shows the transient and SSS pressure profiles 1/2 hour after the startup of a compressor station. 10 to 20 psi errors exist over most of the line.

Figure 3D: Temperature Profile 30 Minutes After Compressor Startup



Steady-state profiles for the same discharge temperature, pressure and average flow are shown in Figure 3D. Thirty minutes after the station comes online, 35 °F temperature errors are still present in the SSS model for most of the downstream section (specifically, for the region the thermal front has not yet reached.) At this point, the thermal component of the line pack error for the SSS model is the dominant source of error. For liquid pipelines the line pack distribution is of less importance, although not negligible. Management of injection and delivery transients on liquid pipelines is done with breakout tankage and with more restrictive scheduling.

PRESSURE MONITORING

The safe operation of a pipeline requires that the pressure stay below the MAOP at all points and all times. For liquid pipelines, the avoidance of slack line flow requires that the pressure always stay above the vapor pressure of the fluid as well. Usually, minimum pressures occur at station suctions and maximum pressures occur at station discharges. Pressures are normally measured at these points.

However, variations in the elevation profiles may produce maximum pressures at low points

and minimum pressures at peaks, where measurements are usually not available. For these points, real-time model calculations can provide the pressures. In addition, off-line models, commonly called look-ahead models in this application, can project pressures at any point and aid an operator in avoiding too high or too low pressures. Since surges produce either high or low pressures, and SSS models do not simulate surges, it is clear that this is an application where transient models are needed.

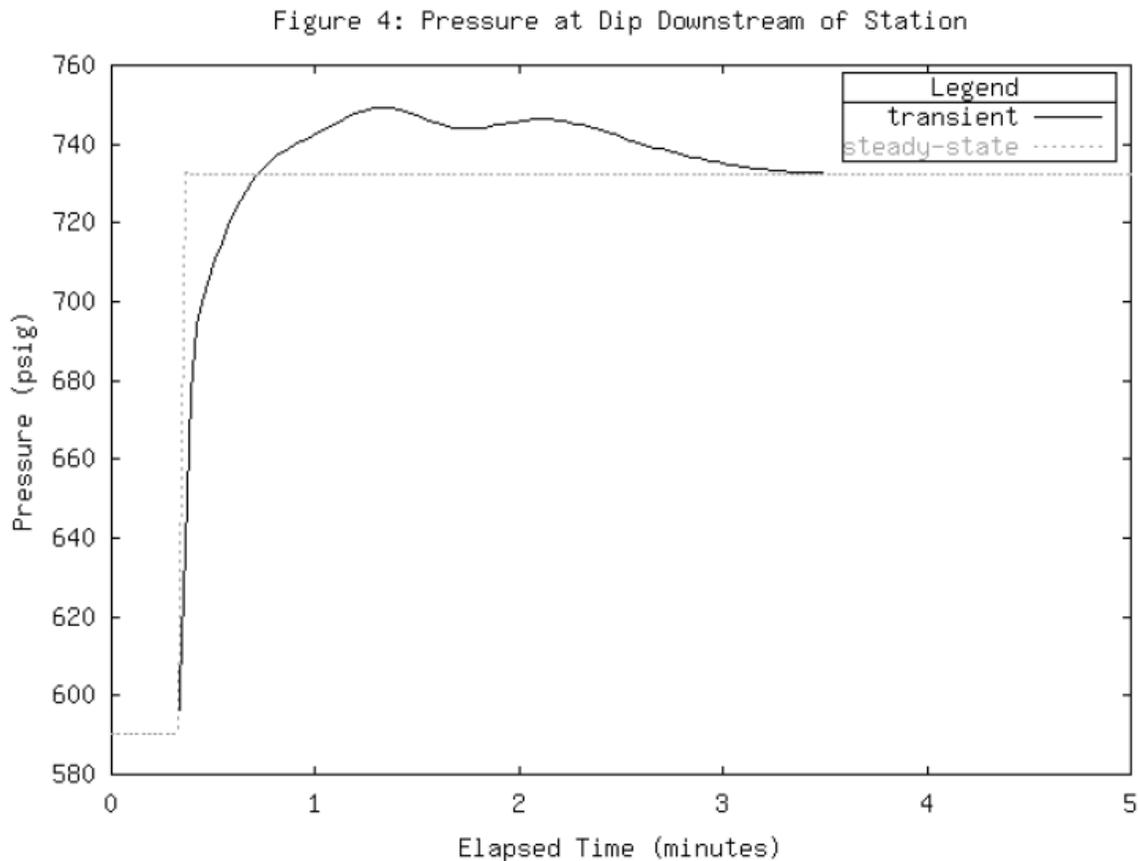


Figure 4 shows the pressure trends resulting from a pump station startup, measured at a low point a short distance downstream of the station discharge, for both SSS and transient models. The model pipeline has been constructed so that the highest pressure in the line is achieved at the low point downstream of the station. The danger of MAOP violation is apparent: the downstream surge can be seen to exceed the SSS model's calculated pressure by 20 psi. (The second bump is a reflection of the initial speed-of-sound surge which has bounced off the model's downstream pressure boundary; this would only occur in a real-world situation if the downstream station was running on suction pressure control.)

DELIVERABILITY

Deliverability is usually a concern of gas pipelines. The word refers to the gas flow rate that can be produced at a delivery point on a pipeline, subject to the initial state of the pipeline and pressure and power constraints. A sustained increase in delivery flow requires a corresponding increase in supply flow. Assuming the supply flow is available, the question is how much time is required to establish a higher equilibrium flow. In an ideal world, the initial higher delivery is made from line pack until the effect of the increased supply flow reaches the delivery point. Some lines operate at times by supplying deliveries entirely from the line pack, with no supply flow at all; in these situations, transient hydraulic effects are all-important. The extent to which these types of operations are possible is a question often analyzed with pipeline flow models.

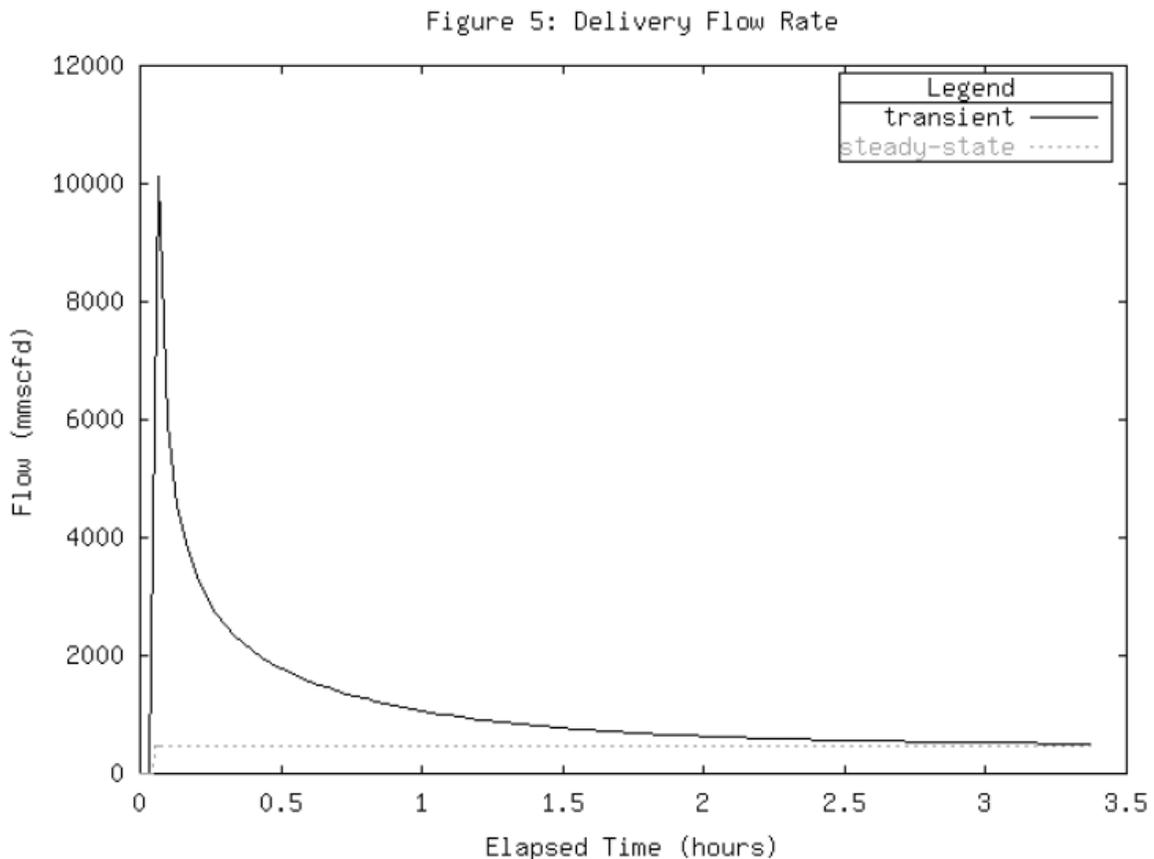


Figure 5 shows the flow that could be produced at a delivery point at a fixed pressure, calculated from SSS and transient models. The delivery is suddenly opened at the downstream station suction at a pressure 70 psi lower than the line pressure at that point 1 minute into the simulation. Note that while very high flow rates could in theory be delivered for very short

time periods as seen here, regulators are generally used to maintain a constant and lower delivery flow. The SSS model gives no information about the achievable short-term delivery flow rate, only the eventual steady-state flow rate. In the case of meeting a delivery purely from line pack, the SSS model would report a maximum achievable flow rate of zero.

PUMP/COMPRESSOR PERFORMANCE MONITORING

Pumps and compressors have performance fluctuations due to changing loads, changing product properties, and wear. A real-time model can assist in detecting these performance changes and in developing correct performance maps over the range of conditions under which the pipeline operates. Accurate performance monitoring is important for proper maintenance of equipment, for optimization, for checking utility bills, and for planning.

Pumps and compressors are supplied with performance maps based on limited testing. These maps have errors to start with, which grow as units wear. Comparison of the performance map with measurements can reveal any errors or changes in the map. If accurate station flow meters are not available (a not uncommon situation), independent inlet and outlet flows can be provided by a real-time model of the pipes entering and leaving the station.

Figure 6: Compressor Performance Map

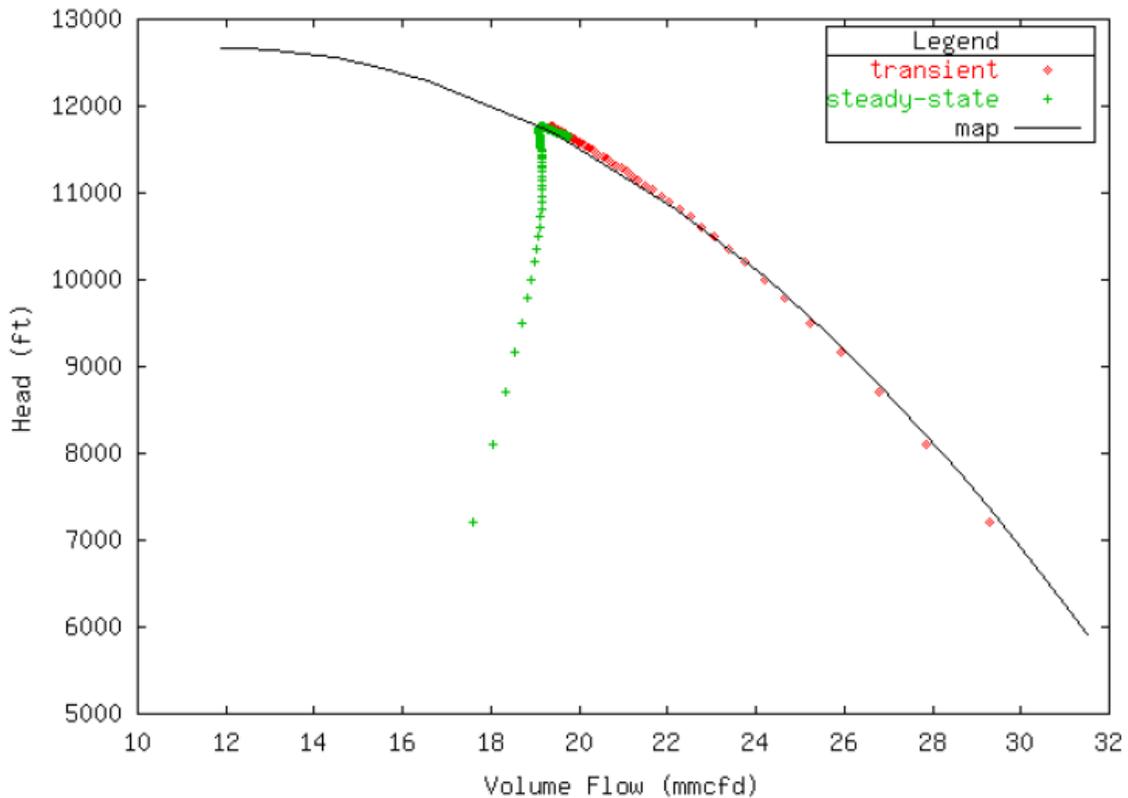


Figure 6 shows calculated performance tracks for SSS and Transient models and, for comparison, the actual map used by both models. These maps are computed in the situation just described, where there is no flow meter on the compressor and so the model computes the compressor flow rate from the modeled flow rate in the upstream segment. This model run includes a period of steady operation and a period of transient operation. It can be seen that during the steady period, both models accurately show the operating point as being on the map, but when there are transients in the line the SSS model produces a wildly inaccurate excursion. This excursion coincides with the period in which the transient model explores most of the map.

Transient models use steady-state calculations for station internal flows, pressures and temperatures. This is because the transients associated with station unit or setpoint changes are too fast for simulation to be practical as part of an overall pipeline simulation. Any difference in the utility of a transient or SSS model would lie in the inlet and outlet flows. For monitoring done on a longer time interval (say, one hour, as is common) using average quantities, there will be little practical difference between a transient and an

SSS model. However, if one is interested in performance at the high flows associated with a pump or compressor start, then a transient model will be required to produce meaningful results as seen above.

CONCLUSION

We have examined SSS and transient solutions to pipeline flow scenarios in the context of several applications: product tracking, line balance, line pack distribution, pressure monitoring, deliverability, and pump/compressor performance monitoring. For product tracking, there is no significant difference between the two types of models (except in pipelines where thermal effects are extremely important such as crude lines). We have also shown that even in crude lines the inaccuracies of SSS models can be largely remedied by using a transient thermal model in conjunction with an SSS hydraulic model.

There are applications where the increased accuracy of the transient model may produce benefits, depending on the details of how the applications are used. These applications include determination of the line pack distribution, deliverability, and pump/compressor performance monitoring. There are other applications where the transient effects are of such importance that SSS models are inadequate. These applications include leak detection based on line balance, where systems using SSS models will have slow response times, and pressure monitoring, where SSS models do not address the problem at all.