PAnORaMA
(Piping Analysis, Operations Research and Maintenance Application)

INTRODUCTION

Fluid Transportation systems may not be as old as alchemy, but are among the few early endeavors where science began to dovetail into engineering. Transportation of water must have been among the first interests and bamboo the first version of pipes.

Industrial piping systems are very vital for the smooth running of any process plant. A cursory look at any modern day refinery or petrochemical complex gives an idea of what a complex network piped transport is needed within a process plant. The design and engineering of a process plant revolves around a whole discipline called piping engineering these days. These professionals with a basic background in chemical or mechanical engineering handle the system design and engineering of these vital transportation systems of process streams from equipment to equipment as well as supply of utility streams such as steam, cooling water, demineralized water, compressed air, etc. So intricate is this design and so perfectly it has to be done for safety as well as economics of any plant, that piping engineering has emerged as a major engineering manpower employer. To support the myriad aspects of piping engineering, enormous codes and standards have evolved over the years.

While the in-plant piping is of the order of kilometers, another transportation system operating at a much larger level, both on capacity as well as pipe length terms, has been making a steady progress. The cross-country piping or sub-sea piping runs for hundreds and thousands of kilometers. These pipelines are as good as any country's infrastructure and the design focus is entirely on transportation related issues such as pressure drop, pump/compressor capacities, location of booster stations, sizing of headers, spur lines and branch lines, etc. The engineering and maintenance issues are quite involved here because, once led, these piping systems are predominantly underground, except surfacing at every 20-30 km distances for monitoring, branching or mixing. Cross-country pipeline transport has grown in leaps and bounds due to the economics it offers over surface transport. It is also piping engineering, but much more exclusive as compared to in-plant piping where equipment take a dominant position as they carry out the main transformation and constitute the major component of capital investment. In a cross-country piping system, everything is piping related.

This paper deals with a simulation software and several applications developed around it, for use by the cross-country pipeline community. The simulation and the applications developed around it support a variety of decision making processes in Piping Analysis, Operations Research and Maintenance. The application draws its name from this (PAnORaMA: Piping Analysis, Operations Research and Maintenance Application).

SIMULATION MODEL FOR FLOW NETWORKS

PAnORaMA has a transient network simulation model at the core of all applications it supports. Steady state performance is arrived at as a culmination of a transient flow situation with input and output specifications of the network kept at constant specifications.

The simulation works for both the fluid types, liquids as well as gases. The governing equations for transient flow of liquids in pipes are very well known and are simply statements of conservation of mass and energy.

The equations relate the flow rate (captured as flow velocity) and pressure to each other and also as functions of location in the pipe along the flow path from some datum location and the time from some user defined zero of time. The governing equations must be satisfied at all times and at all locations in any network of pipes. Colebrook-White equation is used in the simulation model to relate friction factor to Reynolds number.

The equations are solved using finite difference techniques. Each pipe segment is discretized into suitable divisions and so is the time. Choice of convergent time steps as well as divisions along the pipe is a key to get the correct transient performance simulation.

The model equations are valid at all locations in a network also. A network also throws up some more equations where the two streams are mixing, or a stream is splitting into two, or where stream specifications (pressure, flow) are changed / regulated such as at a pump/compressor, pressure reducing station, flow control valve etc. PAnORaMA handles a network essentially by describing it as a tree or loop comprising of segments and nodes. Any network can be created using these two basic building blocks as discussed below.

Nodes in a Network

PAnORaMA has provision for six types of nodes, namely START, END, MIXER, SPLITTER, INTERMEDIATE and EQUIPMENT. Their nomenclature and implication is as follows.

START Node: This is where the network begins. This could be the discharge of a pump which has a suction from a source and which introduces the fluid into the network at a certain specification. The specifications could be time variant or invariant. For example, the entry pressure and/or flow could be steady with time or could vary with time as per user given time series. The specifications serve as necessary initial (and/or boundary) conditions for solution of the governing equations. A complex network could have many sources from which it draws and the network thus could have more than one start nodes. This node is at the extremity of any network and can be categorized as a terminal node.

END Node: This is where a part of the network ends. These are generally the user nodes where a user on the network draws the fluid at certain specifications. The specification could be time dependent or time invariant. For example, the user may draw a flow rate as per a specific time series. The specifications at the end node serve as boundary conditions for simulation as in the case of the START nodes. The number of END nodes could be one or more. END node is also a terminal node as START node.

MIXER Node: This is a location where flows coming from two different pipe segments merge and the combined or commingled flow travels through a single downstream line. These types of nodes are interior nodes as the network does not begin or end at these nodes.

SPLITTER Node: This is the opposite of the MIXER Node. A stream coming from a pipe segment splits into two streams at this node and the two resultant streams travel through two different pipe segments downstream. This is also an interior type of network node.

INTERMEDIATE Node: This could be a location on the network where the pipe size could change or where merely some flow parameter measurement (pressure, flow etc.) is available or is desired. Flow from an upstream pipe section passes down to the downstream section without any change in specification at such nodes.

EQUIPMENT Node: This is similar to INTERMEDIATE node except that it could change a specification of the stream traversing this node, except the flow. It could be a control valve which also causes pressure drop, or a pressure reducing station or a pressure boosting station (Pump, compressor). User needs to specify here the equipment characteristics (power curve of a compressor, pump characteristic curve, downstream pressure set point if it is a pressure reducing station etc. There is no flow change across this node as in the case of INTERMEDIATE Node.

Any network topology can be created by usage of these nodes interconnected through pipe sections.

Segments in a Network

Segment is a second important aspect of a network. A segment is viewed as a pipe section connecting a pair of nodes. Its specification such as diameter, surface roughness and length is to be provided by the user. As mentioned earlier, the user will also provide the number of divisions the segment needs to be divided into for finite difference solution of the governing model equations.

Creation of a Simulation

The segments and the six types of nodes allow the user to create a simulation of any existing or proposed network. The steps involved in creating a network are summarized here.

1. On a sketch of the network, identify the suitable type of each of the node.

2. Number all the nodes starting with 1 and assigning serial numbers without missing any number in between. It is not necessary to start numbering or to number in any particular order (such as left to right etc.). What is essential is that each node must be assigned a unique serial number and the numbers thus used should form a contiguous series of integers starting with 1. A network with N nodes will thus have the nodes numbered from 1 or N.

3. Similarly, number all the segments serially using a contiguous series of integers starting with 1 and covering all the M segments.

4. User then draws the network using built-in drafting facility in PAnOraMA. For each of the nodes, user provides input data such as node type (any one of the six types discussed earlier) and a tag name for identification (such as pump, or user-1 or a location of the node etc.). These tags are used to only make the display and reports readable. Elevation of the node from some datum is also provided. If the node is above the datum, the elevation is positive. For nodes below the datum, the elevation is negative. This is necessary for incorporation of hydrostatic head in the model equations, and is very important for networks transporting liquids.

5. Each network has a specific number of degrees of freedom and user must specify those many stream specifications. For a simplified case, where stream specification is mainly in terms of pressure and flow rate, the degrees of freedom for a tree or loop type network is exactly equal to the number of terminal nodes (START and END nodes). At the terminal nodes, the user must specify pressure and/or flow rate, with the total specifications not exceeding the total number of terminal nodes. For example, if the network is in its minimal form as a dedicated line with one start and one end node only, user can specify (a) pressure at start node and flow at the end node or (b) flow at start node and pressure at end node or (c) pressure and flow at start node or (d) pressure and flow at the end node. At least one of the specifications should be a flow rate and one pressure for obtaining a unique solution.

6. The specification of pressure and/or flow at the terminal node can be a time series giving several times and the parameter value at that time. The application then uses this information and calculates the parameter value by linear interpolation at any in-between instant.

7. For decoding the network topology for developing the model equations, the location of each node in the network has to be specified in terms of the neighboring segments associated with it. This is done through assignment of associated segment number (ASN), not exceeding 3 for any type of node. The six types of nodes, namely START, END, MIXER, SPLITTER, INTERMEDIATE and EQUIPMENT admit 1, 1, 3, 3, 2, 2 associate segments respectively. For example, a start node is connected only with one segment which is downstream of it. An END node is connected with only one segment upstream of it, a MIXER node has two upstream and one downstream segment. A SPLITTER node has one upstream and two downstream segments. INTERMEDIATE and EQUIPMENT nodes have one upstream and one downstream segment associated with them.

8. To aid the solution of the governing partial differential equations, the user also needs to provide initial pressures at all the nodes. These values will depend on the start up philosophy. For example, one may pressurize the network initially without any draw from the network and then ramp up the flows at the

user ends with time to their full potential. In this case, pressure at all the nodes initially will be uniform.

9. The data for each segment is much simpler. User provides the segment length, inner diameter, roughness.

10. As seen earlier, the partial differential equations are solved using finite difference technique and the segments need to be suitably discretized in intervals. The number of such divisions need to be specified by the user. The segment is divided into equal intervals using this number. Each of the location along the segments thus crated is treated as a 'virtual' node. The pressures and flow values are available at each of these nodes in addition to the actual nodes at discrete time intervals.

11. The solution requires the initial flow to be specified along each segment. It will also depend on the startup condition. The flow is considered the same at all virtual nodes of a segment initially and equal to the user provided flow in the segment.

12. Initial pressures at the virtual nodes are similarly calculated by linear interpolation using the user given initial pressures at the nodes at the two ends of a segment.

13. With the above data provided for all the nodes and the segments, the application analyzes the network topology, generates equations in discretized form, and sets up the equations to solve for pressures and flows at all the nodes (real and virtual) at a incremented time from the given or previously calculated values at the current time. The solution marches in time till the pressure and flow profiles are generated for the network up to stipulated time.

14. The user needs to specify whether the fluid is gas or a liquid. If it is a liquid, the important properties such as density, viscosity and bulk modulus of elasticity are provided. If it is a gas, the density and viscosity are provided at some reference pressure. There applicable values at local pressure at any time are calculated using inbuilt correlations. Compressibility data also need to be provided for gaseous systems.

15. To facilitate the simulation, user provides the start time (TSTART), end time (called TMAX) and suitable time interval for discretization.

16. PAnORaMA is for off-line as well as real time usage. The simulation automatically switches to real time after the expiry of the end time (TMAX). The simulation in real time uses terminal node specifications (pressure and/flow) from live SCADA data or user provided time series.

PAnORaMA can be used for transient simulation of the network leading to a steady state. It can be used for water hammer analysis, analysis of sudden or fast closure or opening of a valve, effect of pump shut down and start up etc. It can be used for survival analysis as well as calculation of line pack and shrinkage for a gas transmission line. Using a comprehensive simulation at its core, several usages can be easily built around this virtual network simulation to support a variety of what-if scenarios.

The creation of simulation is very simple and involves drawing the network by dragging and dropping the appropriate types of nodes and connecting them with segments. Populating of data for simulation is through forms which pop-up by clicks on nodes and segments. The results can be viewed along with simulation or post simulation by rewinding. The time series of the pressures and flows can be viewed selectively for nodes and in graphical forms.

The network can be extended to include additional users and suppliers. For this purpose, the node types on an existing network can be changed to draw the incremental additions to the network. The node type changes allowed are comprehensive and complete. This facility allows to build a network gradually and check for its performance before extending it further.

The application can be used for design as well as rating by setting up the simulation and carrying out simulation experiments with it.

One of the major objective of developing this generic network simulator was, however, not these design and rating or analysis and operations research applications only. PAnORaMA has a unique approach to leak detection based on simulation and its comparison with live control room data. This aspect is discussed below.

PIPE NETWORK LEAK DETECTION

Cross-country pipelines run thousands of kms and are a buried and valuable asset of any country or group of countries. As they supply the energy in most cases, they become the life-lines, in a true modern sense. Any leakage in an active pipeline is not only a loss of valuable commodity being transported, it has severe safety implications. Getting alerted to a leakage event within the shortest possible time after the leakage develops, knowing its location within a reasonable range (say +- X m) so that it can be visited, and estimating its quantum (what percent of the commodity being transported is being lost through leakage) is extremely important for any pipeline operator. These three aspects can be termed as leak detection, leak localization and leak quantification. Unfortunately, the simple looking pipeline working on very basic principles of fluid mechanics is a large real life system and in spite of a reasonably sound understanding of the science of fluid flow, the leak detection (and localization and quantification) which is reliable is still eluding us. The false alarms far outnumber the genuine identification instances and/or the accuracy of localization and quantification is not adequate. Also, the reported leak detection applications make several unrealistic demands on operation such as it should be at steady state everywhere in the network or the leak should be more than some (say 2) percent of the total flow etc. PAnORaMA attempts to overcome these problems by using the simulation power and using some concepts of pattern recognition in developing an on-line, real time system which can do the job very scientifically.

The leak detection feature of PAnORaMA is briefly discussed in the following along with its cardinal conceptual philosophy.

Philosophy of Leak Detection

The simulation model of any existing network can be ‘tuned’ using actual performance data to ensure that it captures the current status of the network and is very predictive in nature. PAnORaMA supports such tuning on demand. Once tuned, the simulation becomes a virtual network imaging the actual network and the SCADA data would match predictions from the model running in real time.

Pressures at various nodes in the network serve as a pulse of the network indicating pipeline health. A tuned simulation model would predict pressures at the network nodes which would normally compare with the data reported by SCADA. When the simulation begins to deviate from the field data, it is attributed to some fault that has developed into the actual network. For example, if the simulated and actual pressure differs only at one node and matches everywhere else, it could indicate an instrument malfunction. However, if simulated pressures, which were matching well with field data till certain instant, suddenly seem to deviate from actual pressures all over the network, it indicates a fault which has developed and whose implications are radiating out from some point and engulfing the whole network. It points to an event which has changed the actual system hydraulics, such as a leakage. PAnORaMA compares its predicted pressure profile in the network with reported pressures at all times and creates an alarm when a spreading deviation is seen which is likely to be a leakage.

The leakage would affect the pressure measurements at nodes in its vicinity earlier as compared to far off nodes. PAnORaMA uses the deviation pattern and analyzes it closely to locate the epicenter of the problem (the leak location).

PAnORaMA then confirms the leak location and also its quantum through simulations done with systematically sliding the leak location around such tentatively identified location. The leak is created in the simulation and its magnitude varied so as to match the simulated network performance with the actual network performance. The location and magnitude of leakage which restores the parity between simulation and actual field data is reported.

To speed up the leak localization and quantification, PAnORaMA has a provision to create leakages at several locations, one at a time and see how the network responds to it. The response is captured as a pattern. PAnORaMA maintains through such off-line exercise a response pattern library for different leak locations. As soon as a leak is detected, the field data is used to construct its pattern and the same is compared with pre-created and stored response patterns to arrive at a tentative location quickly. Pattern recognition is used for this purpose.

The leak detection by PAnORaMA is thus based on simulation, pattern recognition and also statistics to some extent. The philosophy is unique and prediction accuracy can be continuously improved by tuning the application through physically and deliberately created leakages as well as leakages that may be caused and confirmed during the network’s life-time. PAnORaMA is a self-learning application in that sense.

Real-time PAnORaMA can also be used as an operator training tool using its additional feature of creating an ‘Emulation’ by giving instrumentation data of the network with their least count, accuracy etc. Emulation can then replace the actual network in which instructor can create changes and faults and see Operator's response. Emulation can also be used to test leak detection capabilities by creating leakage on emulation and serving this data as actual and testing whether the LDS can detect its location and quantum.

PAnORaMA's Leak Detection Capabilities have been extensively tested using such rigorous testing methods. This facility can also be used to ascertain what leak detection accuracy can be achieved given the existing instrumentation accuracy. It can also be used to decide as to what accuracy the instruments should have to detect leakage to a desired accuracy (quantity as well location) in a new project.

The simulation power that PAnORaMA creates and bases its usage on allows any decision making to be rooted in physics and makes it very reliable.