PAnORaMA LDS

(Piping Analysis, Operations Research and Maintenance Application)

Leak Detection System

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ABSTRACT

Cross-country pipelines are used for long distance transportation of liquids and gases due to the improved safety and economics they offer over surface transport such as by road and/or rail. The important commodities often transported and distributed include crude oil, natural gas, several petrochemical products such as petrol, diesel, kerosene, aviation turbine fuel etc. Not less important is the transportation of water (drinking water,

irrigation water, sewage water etc.) through pipelines criss-crossing cities and the country side in the world.

The piping networks are mostly buried over the country side, but could also be laid on the river bed, trough drillings made through mountains, through ducts beneath the railway lines etc. Once laid, these transportation assets do not have the visual inspection facility such as in over ground process plant piping etc. However, the pipelines are susceptible to leakage which could lead to not only the loss of commodity, but also to dangerous situations due to the hazardous nature of the commodity they are designed to carry. Some indirect way of detecting leakages as and when they develop is an essential part of cross-country pipeline’s requirement.

PAnORaMA LDS is a Leak Detection System (LDS) based on transient real time simulation of any operational pipeline network. The simulator as well its LDS is a product of several years of extensive research and practical experience with cross-country fluid transportation networks at the Piping Engineering Cell of Indian Institute of Technology Bombay, a premier institution known globally for its academics and research. The real time simulated performance serves as an ideal reference against which the actual operating data polled at suitable intervals of time (often seconds/minutes) reported to the control room is continuously compared. When the two sets of data (simulated and actual) match with each other, it indicates a fault-free operation. Any mismatch which develops is an alert of a fault that has developed in the transportation system. Depending on how the fault manifests itself in the change in pressures monitored

at several places in the network, an inbuilt intelligence in the software categorizes it as due to isolated instrument malfunction or a leakage. If seen as a leakage, PAnORaMA LDS studies the change in pressure pattern over a small interval after the leakage event (few minutes) and compares the pattern with inbuilt network specific patterns of signatures of different leak locations. The pattern recognition helps locate the leakage and its quantum. The leak event identification, location of the leakage and its quantification use the powerful real time network simulation engine, pattern recognition and artificial intelligence. Because the LDS is based on simulation as a virtual pipe network mimicking the actual network and advanced concepts from artificial intelligence and pattern recognition, it minimizes spurious alarms. The simulator can be periodically validated using actual network performance. As the simulator keeps pace with actual reality, it helps to reduce spurious alarms further once installed in the control room.

The paper discusses the network simulator along with the philosophy behind our Leak Detection System (LDS). Several additional unique features of PAnORaMA LDS, such as its ability to easily incorporate incremental changes in the network as businesses grow, periodically revise leakage pattern library as the pipeline system itself ages in terms of wax deposition, corrosion etc. are also presented in the paper.

Keywords: Leak Detection System, Transient Network Simulator, Leak Pattern Library, Pattern Recognition, Artificial Intelligence, Minimal Spurious Alarms

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 or a steel plant gives an idea of what a complex network of 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 in 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 installed, these piping systems are predominantly underground, except surfacing at every 30-40 km distances for monitoring, branching or mixing (comingling). Cross-country and sub-sea pipeline transport has grown in leaps and bounds due to the economics it offers over surface (land, sea) transport. It is also piping engineering, but much more exclusive as compared to in-plant piping. In the latter, the equipment takes 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. Equipment such as pumps/compressors is incidental as it is required to support the transportation over long distances.

Although buried, and therefore out of sight, over a major part of its length, the cross-country pipe carries no less important a commodity, be it crude oil or natural gas, or finished petroleum products such as kerosene, petrol, aviation turbine fuel, naphtha, etc. Therefore, it carries danger with it and any leakage could potentially lead to a hazardous scenario. It is all the more important to be concerned about it because, unlike process plants which are located in designated industrial areas, cross-country pipelines travel through urban and rural populated areas as well as unsuspecting countryside. Any unnoticed leakage of the commodity has serious consequences for the HSE, Health, Safety and Environment. The cross-country pipelines are not only confined to the above commodities. Water transport, be it for drinking purposes, sewage, irrigation, District

Cooling Systems (DCS) etc., is a very significant application. Whatever may the commodity being transported over distances, constant and effective surveillance is impractical and operators of cross-country pipelines depend entirely on the pressure/flow data from instruments provided for that purpose at above ground stations that are provided at intervals of 30-100 km. Even a trained operator would find it very difficult to analyze the data and arrive at a reliable conclusion that the data indicates a leakage at a particular location and of certain magnitude. Leak Detection based on human intelligence is most likely to be very inadequate. The professional community in the pipeline sector has been on the lookout for a Leak Detection System (LDS) based on some scientific principle and reasoning which alerts about the leakage. There are several technologies proposed from time to time, and there would be many in future.

This paper begins with the description of a generic transient simulator for any flow network followed by a brief overview of the alternative philosophies of leak detection propounded by various researchers with their merits and demerits.

SIMULATION MODEL FOR FLOW NETWORKS

PAnORaMA has a transient network simulation model at the core of its Leak detection System. Our transient 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 as follows (Eq. 1a, 1b). The various parameters in the equations are as described. The equations, when solved, give the liquid velocity (v) and pressure (P) in the pipe as a function of location x (measured from some point, such as inlet) and time t. The equations for liquid flow through pipes are simply statements of conservation of mass and energy that form a system of coupled partial differential equations. The equations are valid for any liquid. For gases, the equations need to be modified to account for their compressibility. The equations are still the statements of conservation of mass and energy.

$$\frac{\partial P}{\partial t} + \rho c^2 \frac{\partial v}{\partial x} = 0 \qquad \text{(Eq. 1a)}$$

$$\frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{f\, v|v|}{2D} = 0 \qquad \text{(Eq. 1b)}$$

where, P is the pressure at location x, v is the fluid velocity at the same location, t is time, c is velocity of sound in the liquid flowing through the pipe, D is the inner diameter of the pipe, ρ is the density of liquid and f is the friction factor.

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. One of the important parameters in the equations is the friction factor f. Literature has several correlations to relate friction factor to Reynolds Number (Re). Reynolds number is a function of pipe inner diameter, fluid velocity (v), fluid density (ρ) and fluid viscosity μ (Eq. 2).

Colebrook-White equation is used as a default equation in the simulation model to relate friction factor to Reynolds Number (Eq. 3).

$$Re = \frac{D\ u\ \rho}{\mu} \qquad \text{(Eq. 2)}$$

$$\frac{1}{\sqrt{f}} = -2\ log\left[\frac{\varepsilon}{3.71D} + \frac{2.51}{R_e\sqrt{f}}\right] \qquad \text{(Eq. 3)}$$

Although this correlation for friction factor f involves iterative solution for a given Reynolds number and pipe roughness factor (ε/D), the choice is mainly governed by the quality of this correlation as well as its acceptability across the professional community dealing in fluid mechanics. However, industry has preference for other correlations as well as Blazius correlation, Panhandle equation etc. PAnORaMA is open to using user preferred correlation instead of the Colebrook White equation.

The governing 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 stream are mixing, or a stream is splitting into two, or where stream specifications (pressure, flow) are changed/regulated such as by a pump/compressor or pressure reducing station, flow control valve etc. PAnORaMA handles a network essentially by describing it as a tree or a loop comprising of segments and nodes. A tree network is one where any location (say a node) has a property that starting from it in any direction and travelling through connected pipe sections, one cannot return to itself. If one or more such path to return exists, then the network is termed as a loop network. For example, a network in Figure 1a is a tree network, while that in Figure 1b is a loop network.

PAnORaMA is applicable to both these types of network. Any network can be created using the two basic building blocks, segments and nodes, as discussed below.

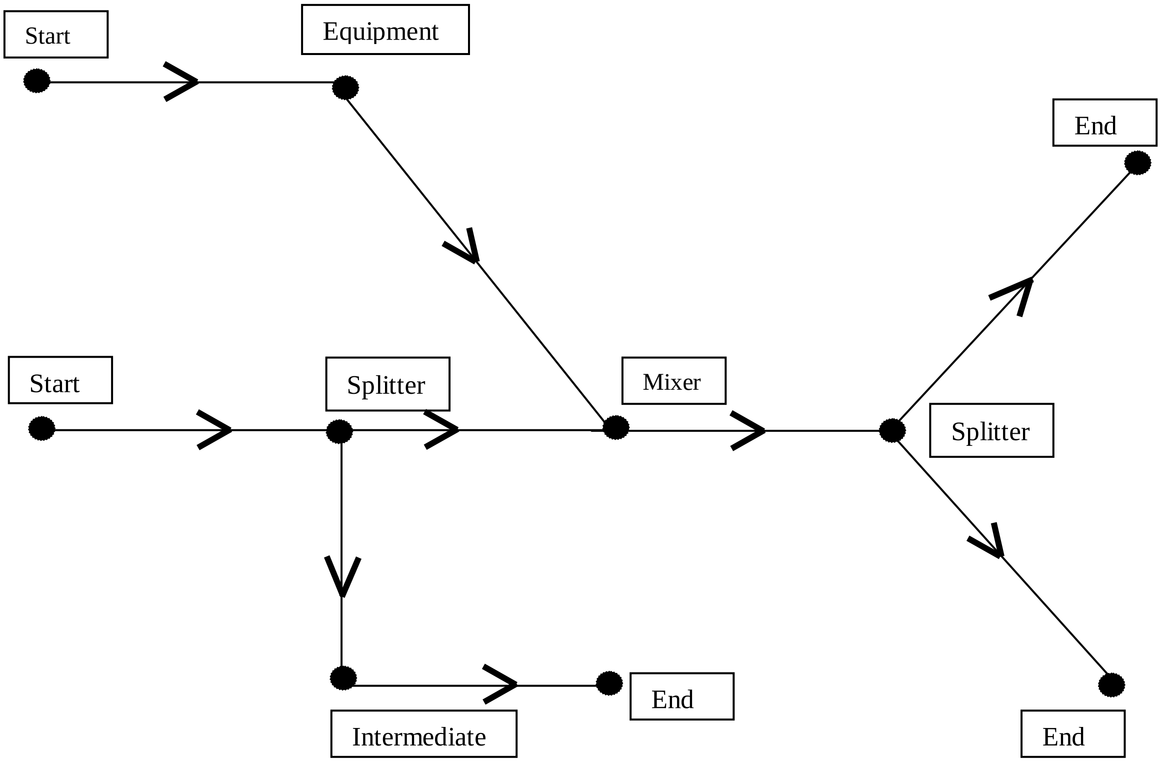


Figure 1a: Schematic of a Tree Network

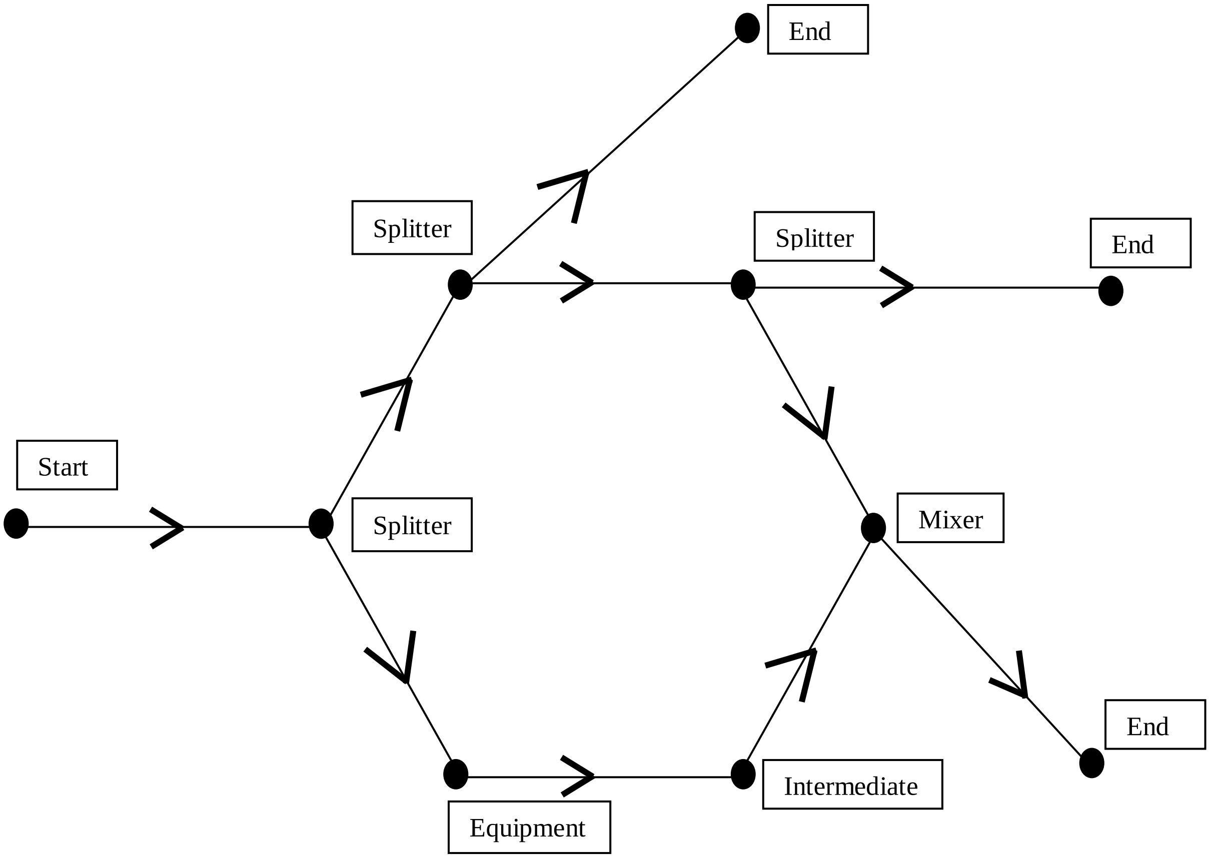


Figure 1b: Schematic of a Loop network

Nodes in a Network

PAnORaMA has provision for six types of nodes, namely START, END, MIXER, SPLITTER, INTERMEDIATE and EQUIPMENT nodes. Their nomenclature and implication are 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 fluid 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 like the START node. If a network has only one START node and one END node, it is obviously the minimal form of a network and is in fact a dedicated line for one user from one source.

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 and/or roughness 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 (pressure, flow rate) at such nodes. This is also an interior type of node.

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 in liquid networks, compressor in gas networks). 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 the second important aspect of a network. A segment is viewed as a pipe section connecting a pair of nodes, one each at its two ends. 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. It may be noted that the length is the actual hydraulic length and not the distance between two nodes the segment is connecting. For example, if one were to drop a thread or chain along the route of the segment from upstream to downstream node and then measure the length of this thread or chain, that is the length travelled by the fluid in this segment. It is often called the 'chainage' in cross-country jargon.

The tree and loop network seen earlier (Fig. 1a, 1b) can be created using the nodes and segments and would look as shown in Figure 2a and 2b respectively.

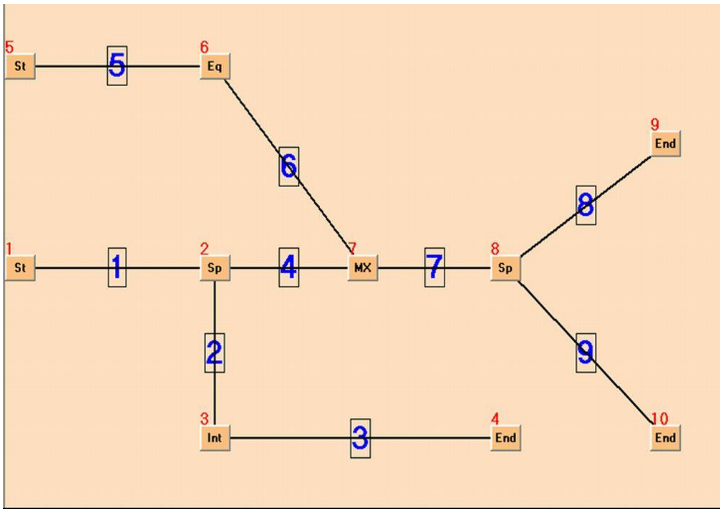


Figure 2a: Tree network in PAnORaMA

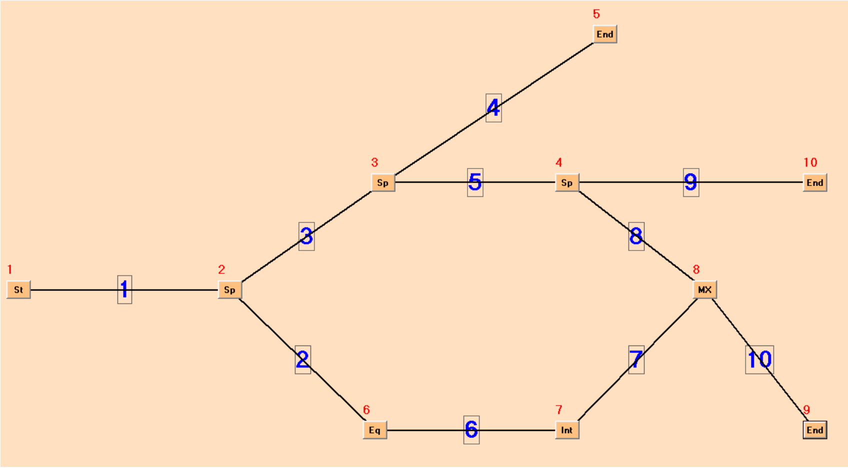


Figure 2b: Loop network in PAnORaMA

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 for transient simulation using PAnORaMA are summarized here.

1. On a sketch of the network, identify the suitable type of each of the nodes.
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 of the network (say M) 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 name 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 nodes can be a time series giving several time values and the parameter value at those times. 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 associated 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. PAnORaMA demands that the user first gives the segment numbers of upstream segments followed by the downstream segments. The network is interpreted and analyzed using this built in expectation. To stress this point further, the ASNs for all the nodes in the network given earlier in Figure 2a are given in Table 1. The table, read with Figure 2a and the above logic is self-explanatory.
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 startup 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 and roughness.

Table 1: Associated Segment Data for nodes

Node Number	Node Type	ASN 1	ASN 2	ASN 3
1.	START	1		
2.	SPLITTER	1	4	2
3.	INTERMEDIATE	2	3	
4.	END	3		
5.	START	5		
6.	EQUIPMENT	5	6	
7.	MIXER	4	6	7
8.	SPLITTER	7	8	9
9.	END	8		
10.	END	9		

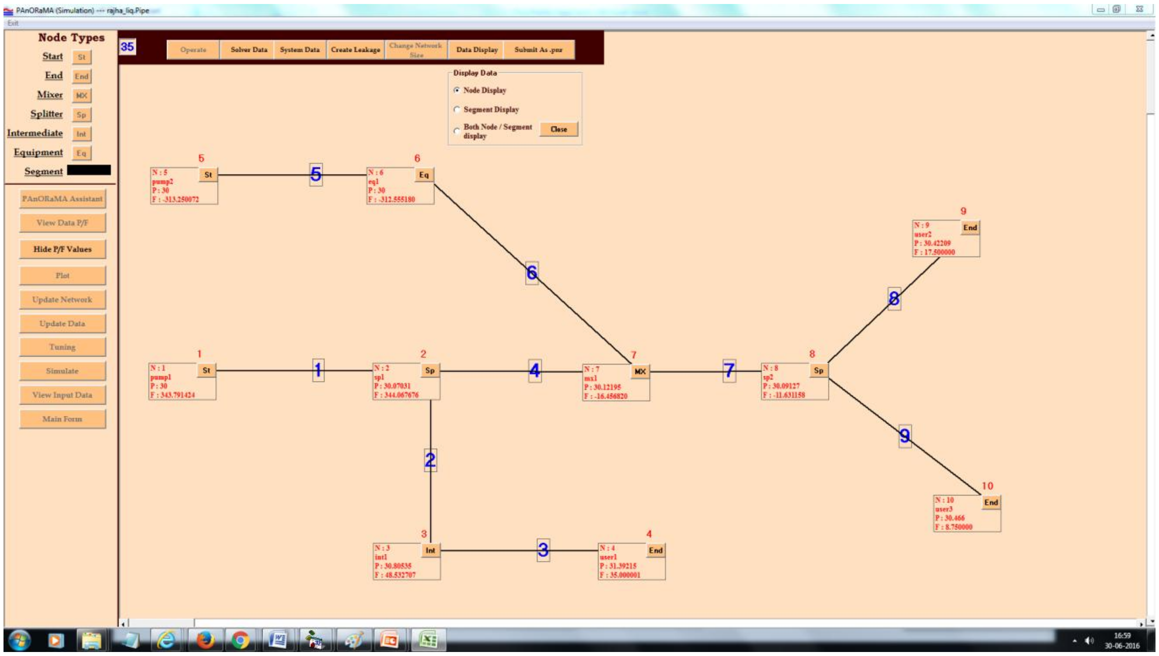
10. As seen earlier, the partial differential equations are solved using finite difference technique and the segments need to be suitably discretized in intervals. The number of such divisions need to be specified by the user. The segment is divided into equal intervals using this number. Each of the location along the segments thus created is treated as a ‘virtual’ node. The pressures and flow values are available after simulation 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. Their 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.

Once the network is coded as per the above instructions, transient network simulation can be carried out in real time as well. This real time transient network simulator forms the backbone of PAnORaMA LDS.

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 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. All simulation results are also available in the spreadsheet form such as in Excel and the user can create his/her own plots for reporting etc.

A representative network as it looks in PAnORaMA environment was presented earlier. During the transient simulation, PAnORaMA displays on this network the pressure and flow at nodes, or at the two ends of any segment, or both. Screen shots of these three types of live results of simulation are shown in Figures 3a, 3b and 3c.



● Node Display
○ Segment Display
○ Both Node / Segment display

N : 1 pump1 P : 30 F : 343.791424

N : 2 sp1 P : 30.07031 F : 344.067676

N : 3 int1 P : 30.80535 F : 48.532707

N : 4 user1 P : 31.39215 F : 35.000001

N : 5 pump2 P : 30 F : -313.250072

N : 6 eq1 P : 30 F : -312.555180

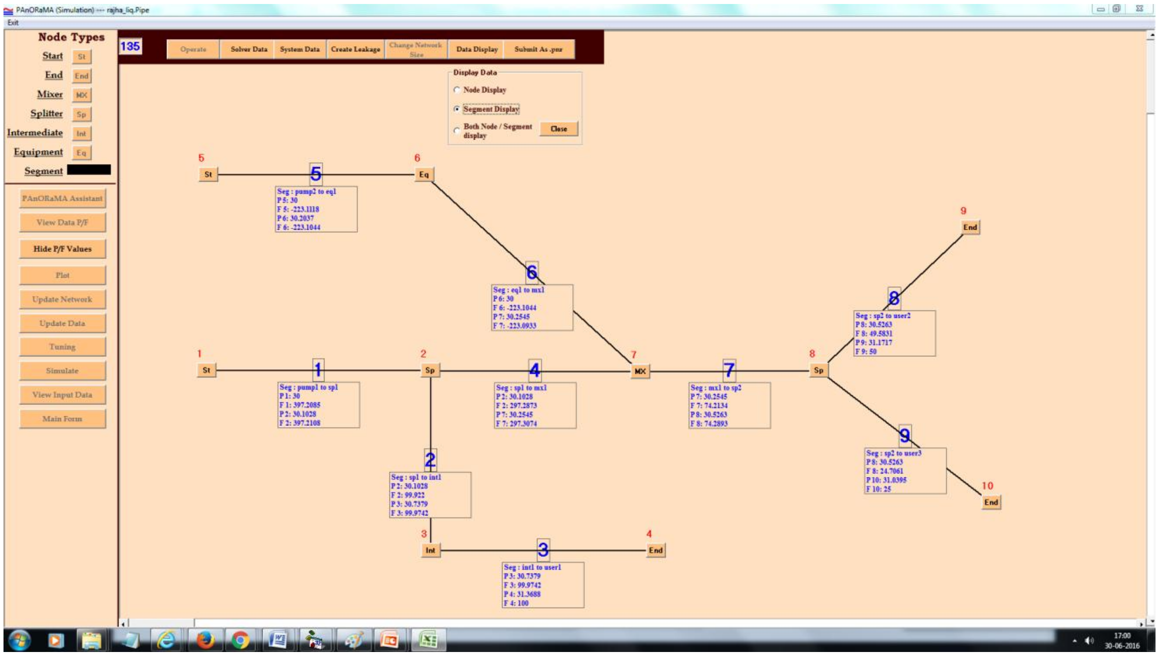
N : 7 mx1 P : 30.12195 F : -16.456820

N : 8 sp2 P : 30.09127 F : -11.631158

N : 9 user2 P : 30.42209 F : 17.500000

N : 10 user3 P : 30.466 F : 8.750000

Figure 3a: Live display of node data



○ Node Display
● Segment Display
○ Both Node / Segment display

Seg : pump1 to sp1 P 1: 30 F 1: 397.2085 P 2: 30.1028 F 2: 397.2108

Seg : sp1 to int1 P 2: 30.1028 F 2: 99.922 P 3: 30.7379 F 3: 99.9742

Seg : int1 to user1 P 3: 30.7379 F 3: 99.9742 P 4: 31.3688 F 4: 100

Seg : sp1 to mx1 P 2: 30.1028 F 2: 297.2873 P 7: 30.2545 F 7: 297.3074

Seg : pump2 to eq1 P 5: 30 F 5: -223.1118 P 6: 30.2037 F 6: -223.1044

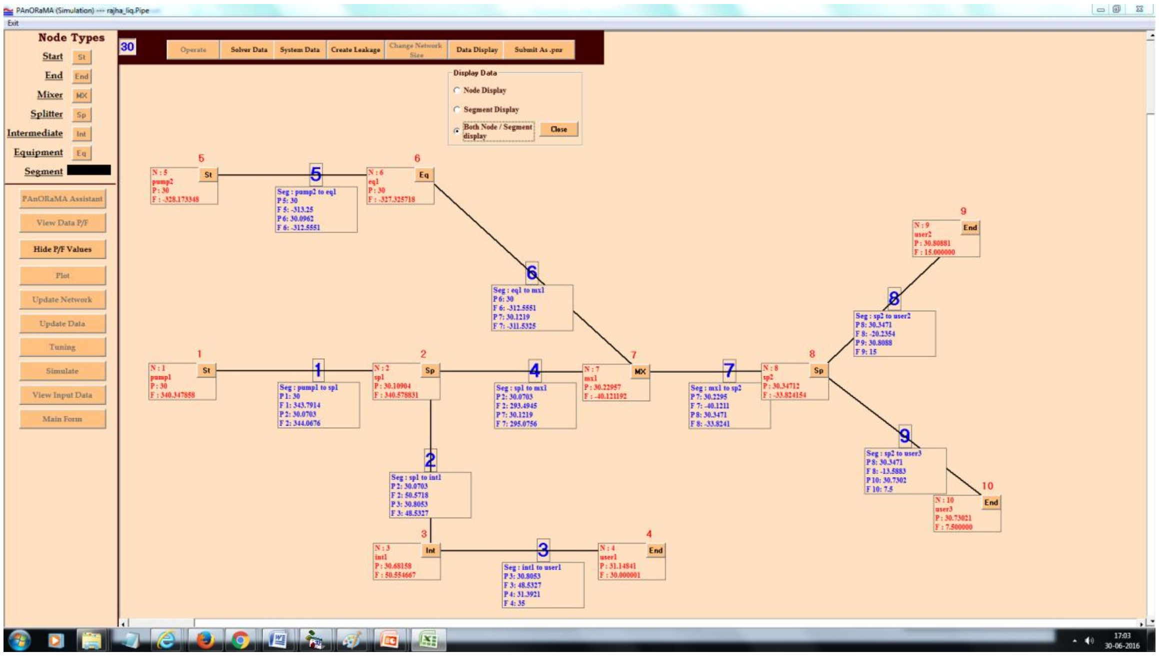
Seg : eq1 to mx1 P 6: 30 F 6: -223.1044 P 7: 30.2545 F 7: -223.0933

Seg : mx1 to sp2 P 7: 30.2545 F 7: 74.2134 P 8: 30.5263 F 8: 74.2893

Seg : sp2 to user2 P 8: 30.5263 F 8: 49.5831 P 9: 31.1717 F 9: 50

Seg : sp2 to user3 P 8: 30.5263 F 8: 24.7061 P 10: 31.0395 F 10: 25

Figure 3b: Live display of Segment data



Display Data
○ Node Display
○ Segment Display
● Both Node / Segment display

5
N : 5
pump2
P : 30
F : -328.173348

5
Seg : pump2 to eq1
P 5: 30
F 5: -313.25
P 6: 30.0962
F 6: -312.5551

6
N : 6
eq1
P : 30
F : -327.325718

6
Seg : eq1 to mx1
P 6: 30
F 6: -312.5551
P 7: 30.1219
F 7: -311.5325

1
N : 1
pump1
P : 30
F : 340.347858

1
Seg : pump1 to sp1
P 1: 30
F 1: 343.7914
P 2: 30.0703
F 2: 344.0676

2
N : 2
sp1
P : 30.10904
F : 340.578831

4
Seg : sp1 to mx1
P 2: 30.0703
F 2: 293.4945
P 7: 30.1219
F 7: 295.0756

7
N : 7
mx1
P : 30.22957
F : -40.121192

7
Seg : mx1 to sp2
P 7: 30.2295
F 7: -40.1211
P 8: 30.3471
F 8: -33.8241

8
N : 8
sp2
P : 30.34712
F : -33.824154

8
Seg : sp2 to user2
P 8: 30.3471
F 8: -20.2354
P 9: 30.8088
F 9: 15

9
N : 9
user2
P : 30.80881
F : 15.000000

9
Seg : sp2 to user3
P 8: 30.3471
F 8: -13.5883
P 10: 30.7302
F 10: 7.5

10
N : 10
user3
P : 30.73021
F : 7.500000

2
Seg : sp1 to int1
P 2: 30.0703
F 2: 50.5718
P 3: 30.8053
F 3: 48.5327

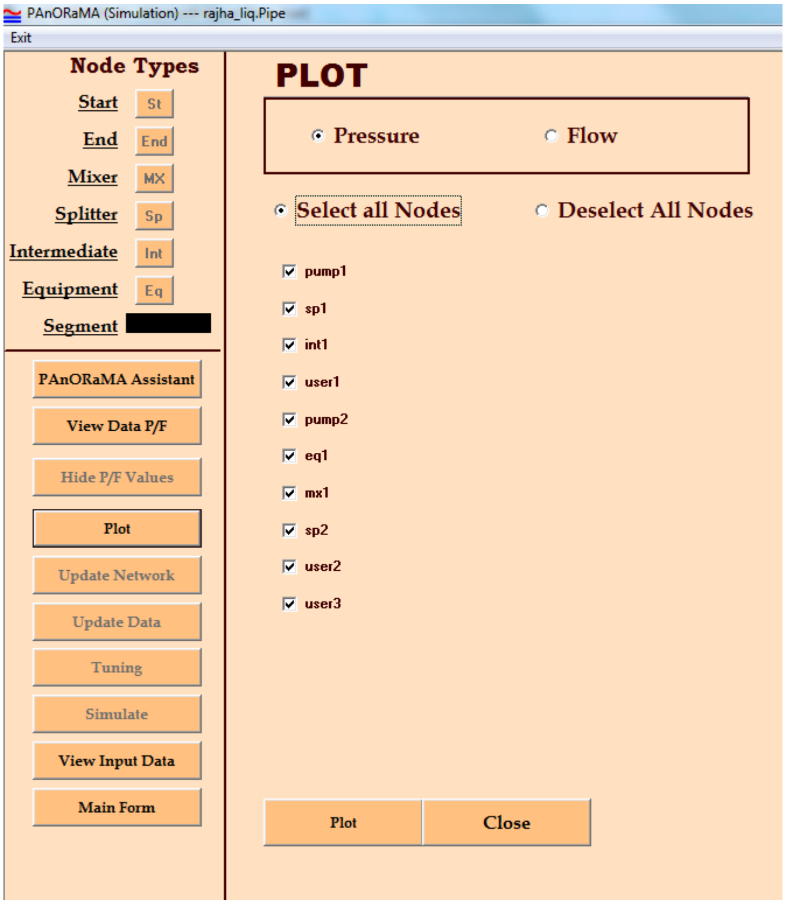
3
N : 3
int1
P : 30.68158
F : 50.554667

3
Seg : int1 to user1
P 3: 30.8053
F 3: 48.5327
P 4: 31.3921
F 4: 35

4
N : 4
user1
P : 31.14841
F : 30.000001

Figure 3c: Live display of both Node and Segment data

The results can also be seen post-simulation by plotting pressures at one, all or selected nodes over the entire simulation time as shown in Figure 4a and Figure 4b. Similarly, flow rates passing a node can also be plotted with time for post-simulation analysis as shown in Figure 5a and 5b.



● Pressure ○ Flow

● Select all Nodes ○ Deselect All Nodes

☑ pump1
☑ sp1
☑ int1
☑ user1
☑ pump2
☑ eq1
☑ mx1
☑ sp2
☑ user2
☑ user3

Figure 4a: Selection for Pressure plots

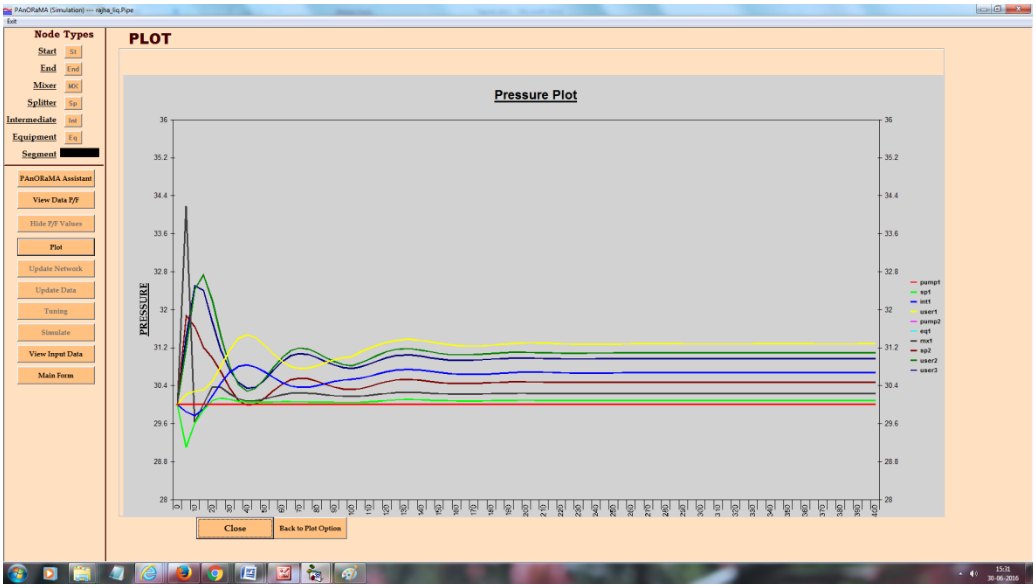
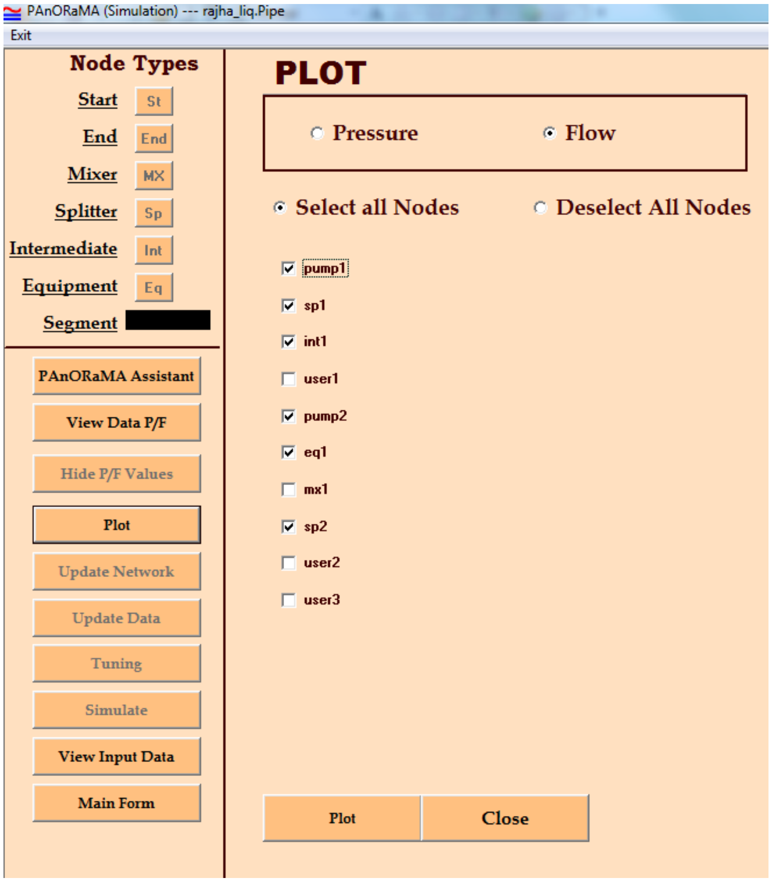


Figure 4b: Graphical display of Pressure plots



○ Pressure ● Flow

● Select all Nodes ○ Deselect All Nodes

☑ pump1
☑ sp1
☑ int1
☐ user1
☑ pump2
☑ eq1
☐ mx1
☑ sp2
☐ user2
☐ user3

Figure 5a: Selection for Flow plots

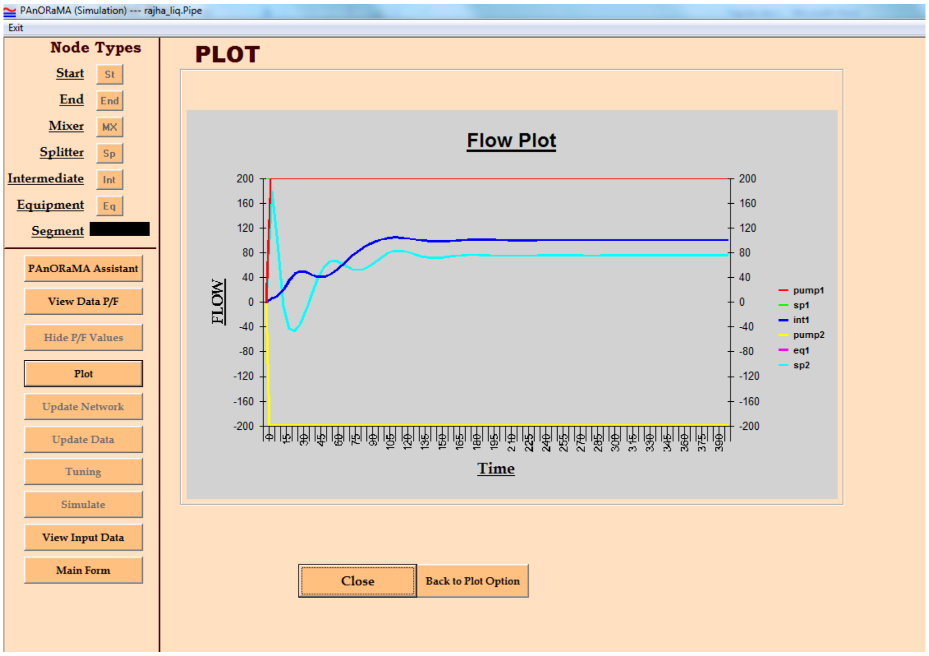


Figure 5b: Graphical display of Flow plots

The same data can also be viewed for each individual node by a right click on the node itself and selecting pressure or flow rate as choice. There is also a facility to watch the results by incrementing time by one step in forward and backward direction (see Figure 6). Various ways of viewing simulation results aid in using PAnORaMA as a design tool as well as a diagnostic tool.

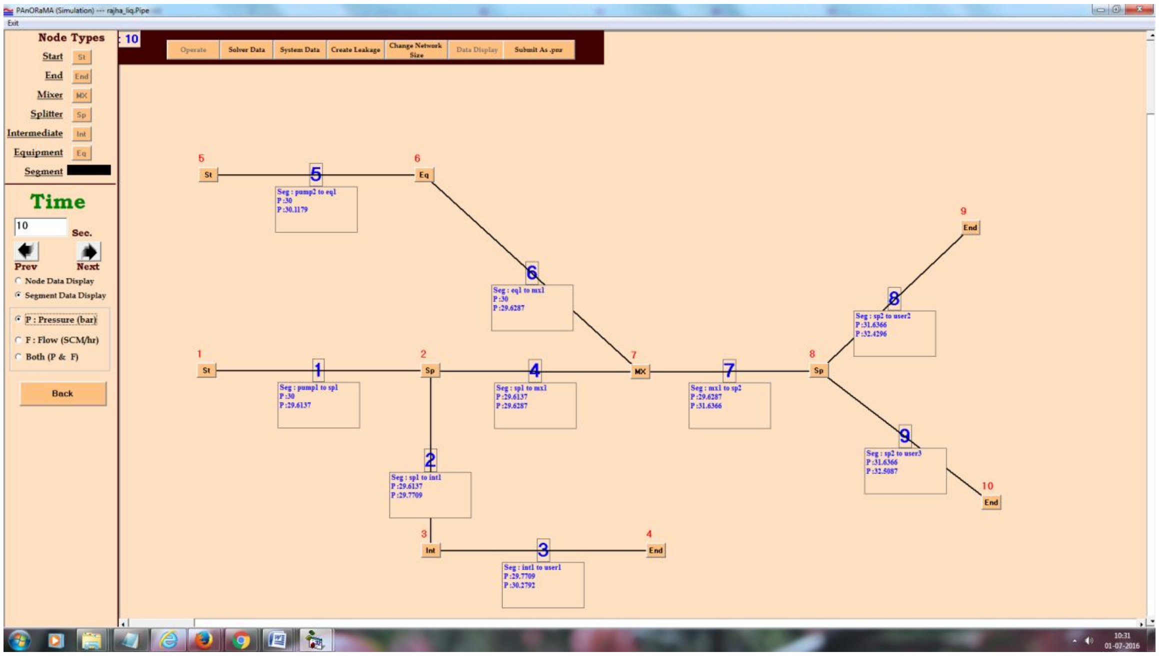


Figure 6: Post simulation viewing of results

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 which are allowed are comprehensive and complete. This facility allows to build a network gradually and check for its performance before extending it further. The available possibilities for changing a node type of a network already created are tabulated in Table 2.

Table 2: Possibilities of changing node types

S. No.	Existing Node Type	Possible Changes
1	START	INTERMEDIATE, MIXER, SPLITTER, EQUIPMENT
2	END	INTERMEDIATE, MIXER, SPLITTER, EQUIPMENT
3	MIXER	No Change Possible
4	SPLITTER	No Change Possible
5	INTERMEDIATE	MIXER, SPLITTER, EQUIPMENT
6	EQUIPMENT	INTERMEDIATE, MIXER, SPLITTER

PAnORaMA has a unique approach to leak detection based on transient simulation and its comparison with live control room data. This aspect is discussed below.

PIPE NETWORK LEAK DETECTION

Cross-country pipelines run thousands of kilometres 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 serious 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 a real time system which can do the job very scientifically. However, before discussing that, a brief description of some of the leak detection philosophies is presented below.

Several technologies, primitive to state-of-art, are available for leak detection in cross-country pipelines. These are briefly presented below.

1. Volume Balancing

Any transportation network has source points where the metered quantities of fluid commodity enter the network, and delivery points where metered quantities are delivered to the customers. If the network is leak proof, there should be no difference between the total incoming and total outgoing quantities. The volume balancing method works on the discrepancy between these two quantities, if any, and attributes it to leakage in the network and then decides the location and quantum of leak through simple steady state pressure drop calculations for the network.

This is the oldest leak detection technology and continues to be offered even today to unsuspecting operators.

2. Negative Pressure Wave

This is another method where pressures are monitored continuously at closely spaced points along the network. In a smoothly functioning network, pressure decreases along the direction of flow. This is basic physics. A leakage, whenever it happens disturbs this expected pressure gradient, which is then analyzed for leak identification.

Unlike the volume balancing method which often works off-line, this method operates in real time.

The method ignores the fact that a network performance is never at steady state due to changes in incoming/outgoing flow rates. The method is known to give spurious alarms due to this reality of real life cross-country pipeline transportation.

The accuracy of the method depends almost directly on the distance between consecutive pressure monitors along the pipe route. The price to be paid for heavy instrumentation can be prohibitive.

3. Acoustic Emission

Any leak from a pressurized pipeline generates a low frequency sound due to the escaping fluid. This hissing sound is detected by travelling along the pipeline with acoustic detectors.

Such a method is useful as a surveillance tool or as a tool to actually pinpoint the exact location after some other tool has indicated a leakage over a range of pipeline length.

4. Fibre Optics

A leakage causes vibrations (that is why the leak makes noise). This vibration is also imposed on the pipeline itself and changes its own frequency of vibration. Also, a leakage could cause change in temperature of the soil around the leakage. For example, if natural gas flowing through a pipeline at high pressure leaks somewhere, it will cool significantly by the so called Joule Thomson effect (often reaching subzero temperatures). This will cool the pipe and the surrounding soil locally. Change in either temperature or vibration frequency can cause change in refractive index of the optic fibre run on the exterior of the pipe along its entire length. This is used in this technique to identify a leakage event.

In a transient network, change in flow rates and the corresponding changes in pressure can cause vibrations in pipe. This itself can alter optic fibre's refractive index. The method is thus ridden with the curse of spurious alarms.

The method requires to be adopted at the time of construction itself as the optic fibre is laid along with the pipe at the time of construction.

5. Copper Wire

For water carrying pipelines, this technique runs a continuous copper wire along the entire length of the pipeline. If water leaks out, the electrical conducting copper wire's resistance changes. The change in current carrying capacity of the wire is seen as pointing towards leakage.

The copper wire responds to any water that comes in contact with it. It could be due to other reasons external to the pipe such as from a nearby drain or even rain. The technique is therefore ridden with possibilities of spurious alarms more than any other technique.

6. Transient Simulation

All transportation networks, operate under significant transients. This is so because of multiple incoming (source) and outgoing (customer) points. Change in pressure and/or flow rate at any one of them will affect the entire network. In gas networks, the transients due to any change affect the network over a longer period of time due to compressibility of the medium. At the same time, the intensity of disturbance gets mitigated by the compressibility. It is unrealistic to expect any network to operate at steady state at any time.

This unsteady state or transience is captured by transient simulation of the network. Once validated, a network simulation behaves as the actual network would do in terms of pressures at various locations in the network. Any deviation in the prediction of pressures made by the simulator and the actual pressures reported by pressure monitoring instruments along the pipeline is a sure indicator of some fault in the network. If the fault seems to affect the transient pressure profiles at various locations in a particular pattern, it indicates with some degree of certainty the occurrence of leakage. The transient simulator then can fine tune the leakage location and quantum through rigorous simulation if necessary.

This transient model based approach stands the best chance of leak detection and avoidance or minimization of spurious alarms.

Most of the Leak Detection Systems being in use are not based on transient simulator. They are based on statistics, or simple volume balancing or expensive instrumentation along the pipeline etc. To the end user, what matters is:

. The speed of detection and alarm of a leakage event after it occurs,

. The accuracy of leak location within acceptable limits so that corrective measures can be taken by excavating soil over a limited length of the buried pipeline and carrying out the necessary repair and

. Quantifying the leakage in terms of the rate at which fluid is leaking out of the network.

Comparison of various LDSs based on various leak detection philosophies from user perspective is presented in Table 4.

Table 4: Comparison of Leak Detection System

Parameter	**Volume Balancing**	**Negative Pressure Wave**	**Acoustic Emission**	**Fibre Optics**	**Copper Wire**	**Transient Simulation**
Tolerant to operating fluctuations in pressure/flow	No	No	Yes	No	Yes	Yes
Applicable to Gas and Liquids both	No (Liquids mostly)	Yes	No (Gas mostly)	Yes	No (Liquids only)	Yes
Makes additional demand on instrumentation/provisions other than required for network operation	No	Yes	No	Yes	Yes	No
Handles both the tree and loop networks	No	Yes	Yes	Yes	Yes	Yes
Likelihood of spurious alarms (high/low)	High	High	Low	High	High	Low
Based on transient simulation of network	No	No	No	No	No	Yes
Needs to be provided for at the design stage	No	Yes	No	Yes	Yes	No

PAnORaMA LDS

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 (or can be made to match through tuning) 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 (in simulation) 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, random noise 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. This facility can also be used to test other third party LDS tools already installed on any given network.

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 LDS feature of PAnORaMA needs a network simulation to be created as a first step. Once this is done, Leak Pattern Library which captures the signature of the impact of leakage at different locations (virtual nodes) can be created. The leakage is simulated by visualizing it as a valve opened at the leakage location. The quantity of leakage is regulated by the coefficient of this valve. The user also has a facility to specify the environment outside the pipe at the leak location because that also has impact on actual leakage rate. For example, if the pipe is laid on a river bed or sea bed and is under hydrostatic pressure exerted by the water column, the leakage flow rate will be less as compared to when the pipe is exposed to atmosphere at the leakage location. The facility is provided wherein the user can create a pattern library by specifying these factors which govern the net rate of leakage. Figure 7 shows a form to specify the data before launching the pattern library creation.

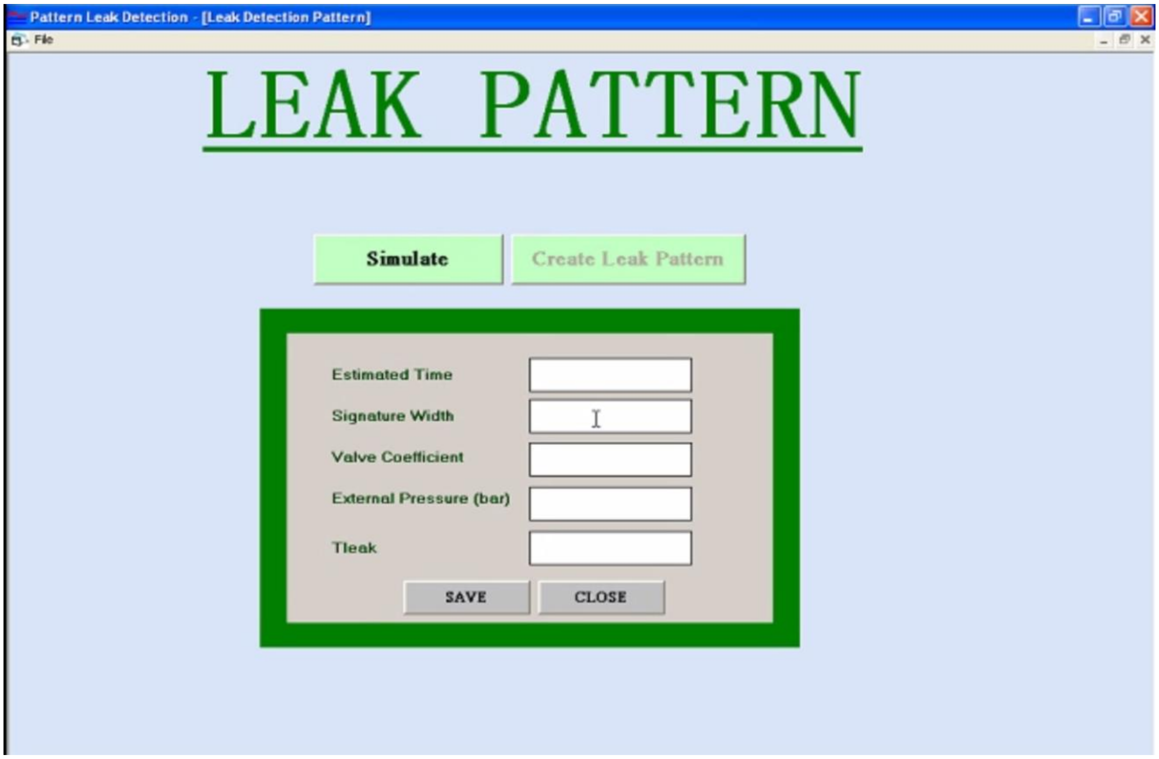


Figure 7: Pattern library creation

Once this preparatory work is done, the application is ready for leak detection. As and when the leak occurs, the LDS predicts the leakage event within a short time and displays its possible locations with their estimated confidence ratings. A typical screenshot when a leak is found is as shown in Figure 8a. The location with the highest confidence rating is what should invite immediate action as shown in Figure 8b. If the best confidence rating itself is poor, the alarm could be ignored by the operator. What is a spurious alarm will evolve over time as the LDS trains itself over a period of time by tuning the simulation backbone by using actual operating data periodically.

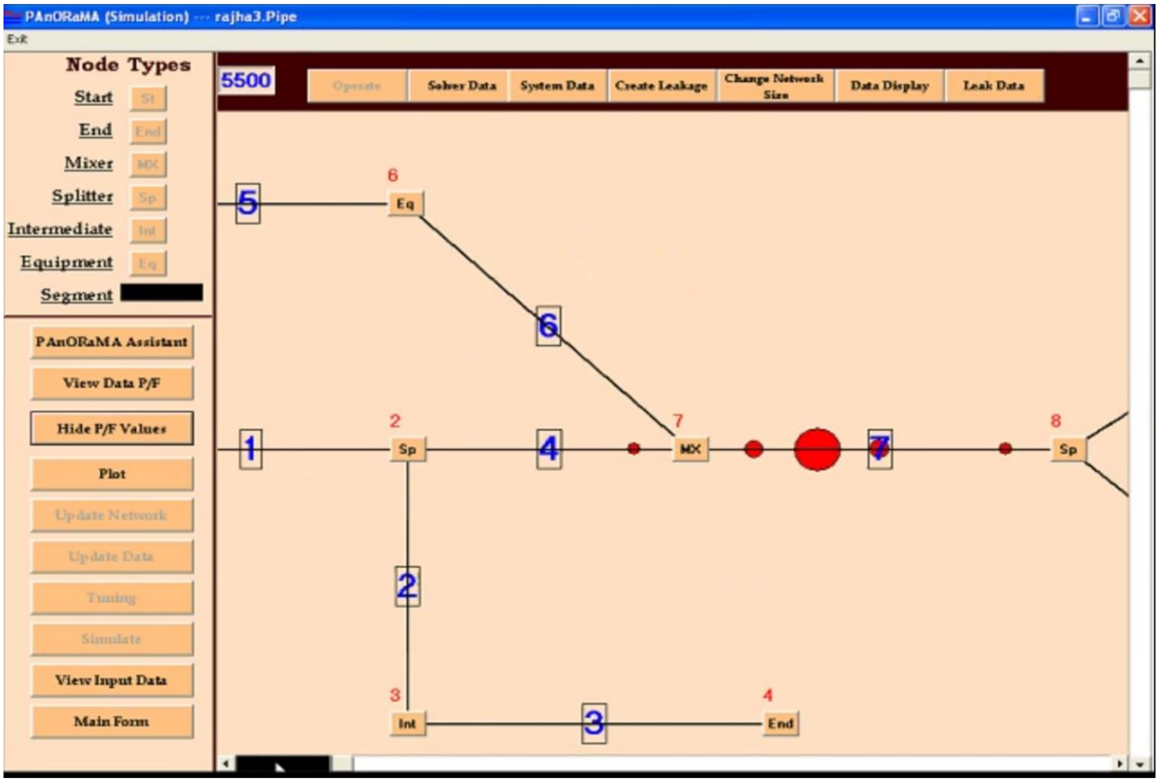
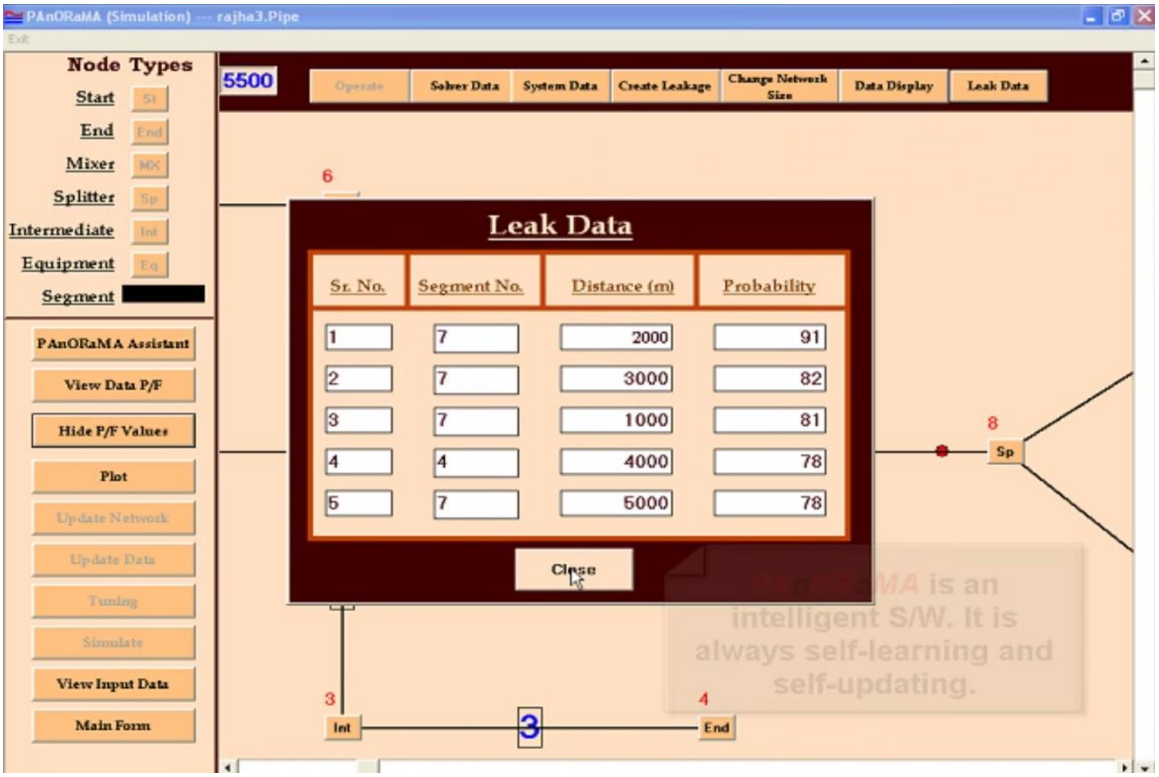


Figure 8a: Display of leak location on network



Leak Data

Sr. No.	Segment No.	Distance (m)	Probability
1	7	2000	91
2	7	3000	82
3	7	1000	81
4	4	4000	78
5	7	5000	78

PAnORaMA is an intelligent S/W. It is always self-learning and self-updating.

Figure 8b: Display of confidence levels in leak location

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.

PAnORaMA has been successfully tested on a petroleum product carrying dedicated pipeline as well as a very complex chilled and hot water carrying piping networks of a District Cooling System involving over 50 users.

CONCLUSION

A comprehensive transient simulation tool, PAnORaMA was presented which is the core engine of PAnORaMA LDS. The paper discussed various alternative technology available today for leak detection and commented on their strengths and weaknesses. A leak detection philosophy based on a transient simulation of a network was discussed as implemented in PAnORaMA LDS.