

# **PAnORaMA Design**

**(Piping Analysis, Operations Research and Maintenance Application)**

**Design Version**

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## **ABSTRACT**

The paper discusses a transient simulator for network flow of gases and liquids. Flow networks are used extensively in process plants, power plants and several other manufacturing plants to distribute utilities such as steam, compressed air, instrument air,

cooling water, de-mineralised water etc. Flow networks or point-to-point (also called dedicated) pipelines are also used for liquid or gas transport over longer distances such as in cross-country pipelines used to transport crude oil, natural gas, petroleum products (petrol, diesel, kerosene, aviation turbine fuels, LPG, etc.) and water (drinking water, sewage water, irrigation water, chilled water for district cooling etc.). Design of these systems in terms of sizing of pipes used as trunk (header) line, spur lines, branch lines has a strong bearing on operability and project economics. With cities mostly getting their cooking gas as piped gas, City Gas Distribution (CGD) systems are very complex pipe networks. With residential buildings going skywards, water and gas networks even at the building level require rigorous design in terms of most economic pipe sizing and layout. Ships have very complex flow networks and ship building involves piping system design. The network flow calculations involved in all these tasks are beyond the realm of calculations using simple spreadsheets and involve solution of highly non-linear simultaneous equations. Use of a comprehensive network simulator is the only way to design such networks.

Liquid carrying pipeline networks suffer from adverse effect of sudden valve closure, pump start-up or shut-down in terms of water hammer effect leading to pipe rupture, vacuum creation due to pump failure and resultant pipe implosion etc. Rigorous water hammer analysis and pressure surge analysis using a transient network simulator must be carried out to design a fail-safe system.

All these design tasks are supported by our PAnORaMA Design application. A transient network flow simulator applicable to single phase flow of gases or liquids is the heart of this application. Pressure drop calculations which form the core step in all these applications are done using standard correlations such as Colebrook White equation. Other correlations for specific applications such as Blazius, Panhandle correlations can be easily incorporated.

For gas distribution networks, PAnORaMA Design has a rigorous shrinkage and line pack calculation procedure which can handle these two key aspects of calculations related to day-to-day commerce for operators of such network. Conventional calculations of line pack and shrinkage often lead to erroneous estimates and billing disputes.

The paper discusses the methodology used in the transient simulation and various applications that the simulator can support. The paper also discusses the intuitive GUIs for user inputs, a GUI for coding network topology, the equations that are internally generated and solved, the various options for viewing simulation results as well as report generation etc.

**Keywords: Flow Network, Pressure Drop Calculations, Pipe Sizing, Water Hammer, Pressure Surge Analysis, Line Pack Calculations, Shrinkage calculations**

## **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.

Hydraulic design of piping systems, in-plant or cross-country or subsea, which are employed for short distance or long distance transportation of gases, vapors or liquids is a very important design task carried out very early in any project. Inadequate design, especially the pipe sizing and pump/compressor rating, can lead to process related issues such as excessive pressure drops, inability to reach design capacity and performance specifications, pipe failure due to excessive pressures created by water hammer effects, fatigue failure due to periodic pressure surges etc. Most of these problems have their roots in wrong or oversimplified hydraulic design. PAnORaMA Design has been developed to support most design tasks of dedicated piping systems or piping networks.

This paper deals with a simulation software for network flow of gases as well as liquids and several applications developed around this simulation tool, for use by the process plant designers, power plant designers, ship builders, municipal water handlers (drinking, irrigation, sewage, chilled water for district cooling etc.) and cross-country pipeline community. The simulation and the applications that can be 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 of the network kept at constant specifications. It is also possible to calculate steady state performance directly by setting time derivatives to zero. That is a fairly straight forward solution procedure and can be provided almost free, at least by us. Compared to transient simulation, that is as good as a nursery school application. It is not discussed further in this paper.

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.

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

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

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,  $\rho$  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 ( $\rho$ ) and fluid viscosity  $\mu$  (Eq. 2).

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

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

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

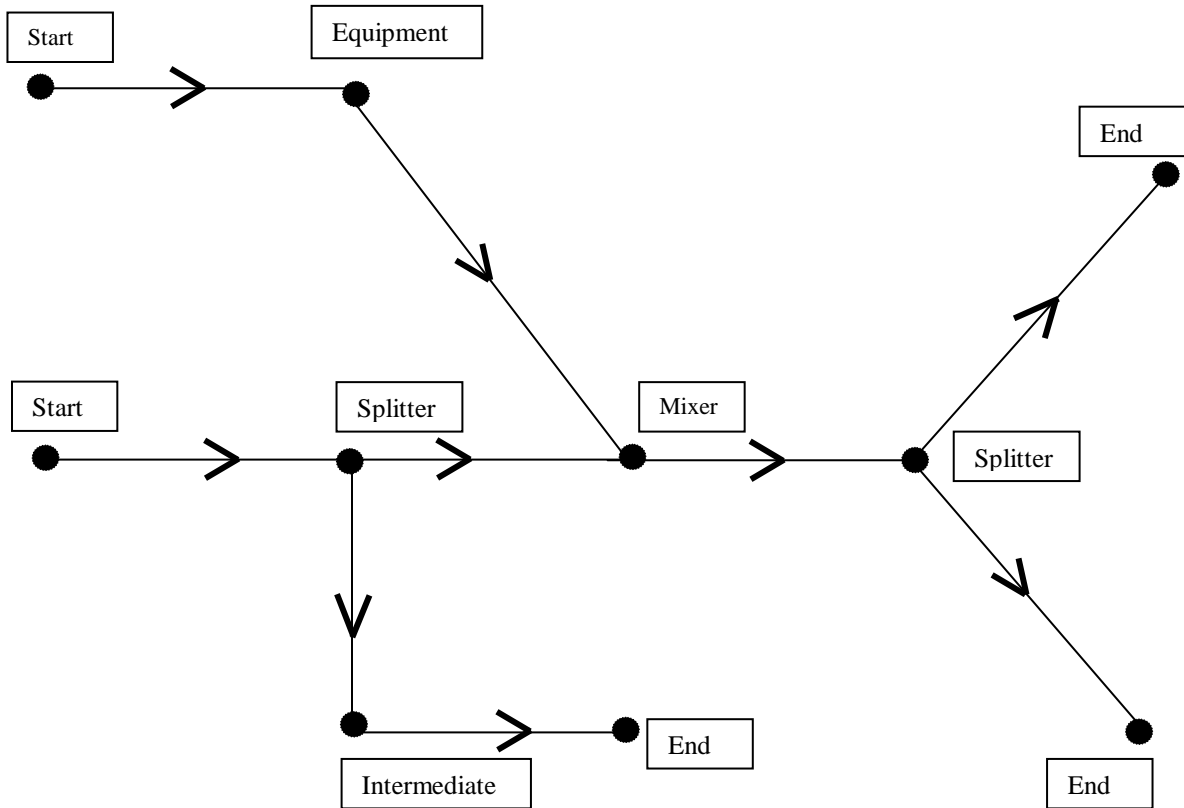
Although this correlation for friction factor  $f$  involves iterative solution for a given Reynolds number and pipe roughness factor ( $\varepsilon/D$ ), the choice is mainly governed by the quality of this correlation as well as its acceptability across the professional community dealing in fluid mechanics. However, industry has preference for other correlations as well as Blasius 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.

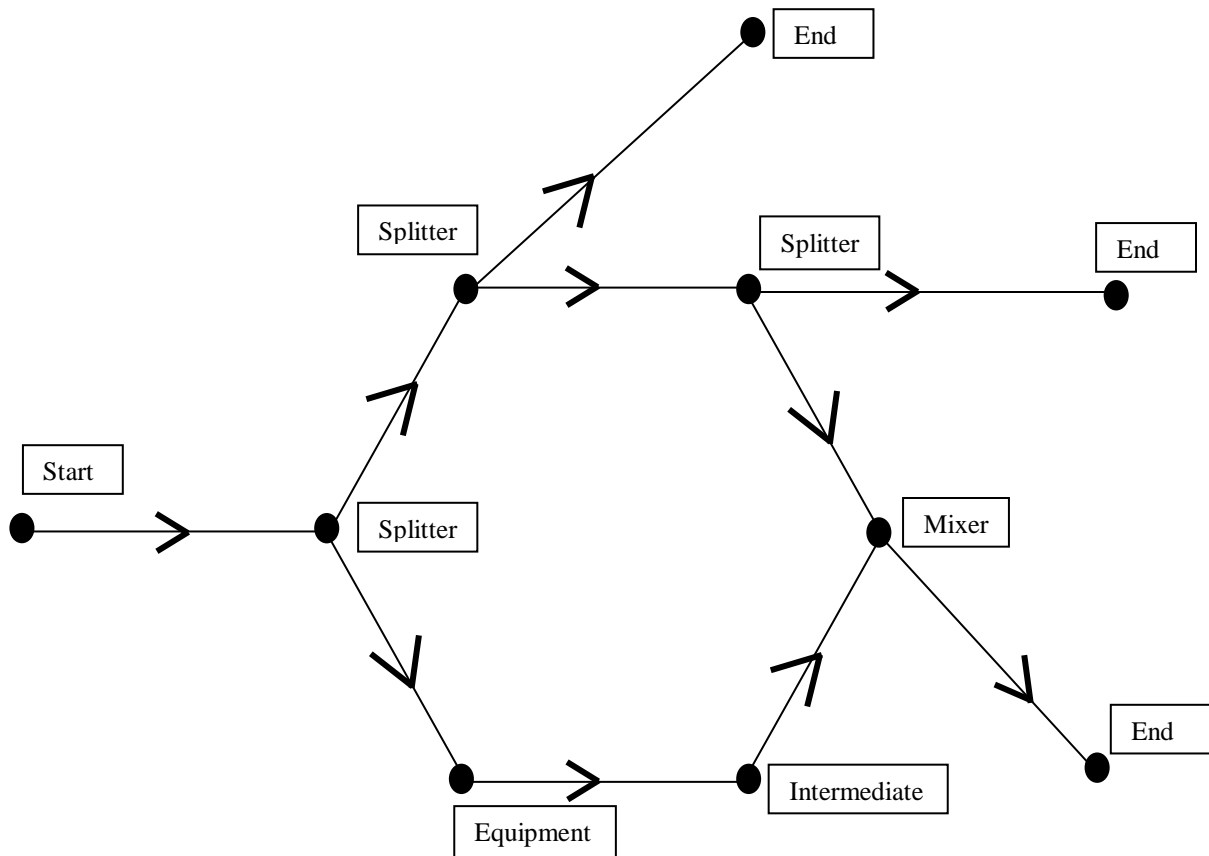


**Figure 1a: Schematic of a Tree Network**

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.

## 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.



**Figure 1b: Schematic of a Loop network**

**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.

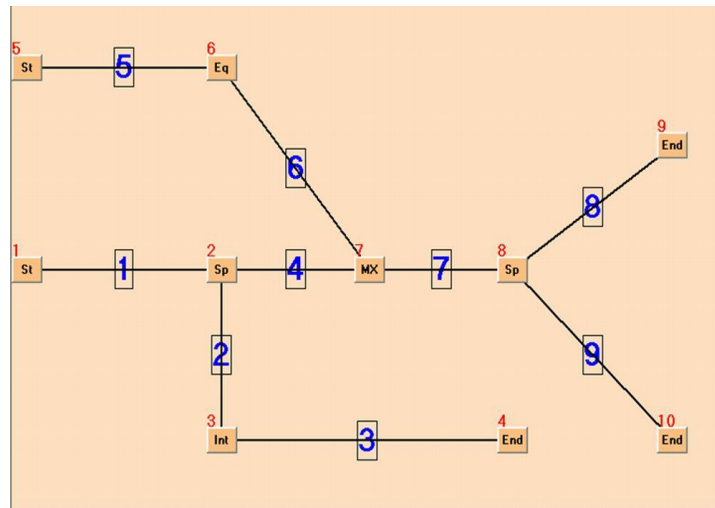
Any network topology can be created by usage of these nodes interconnected through pipe sections.

### **Segments in a Network**

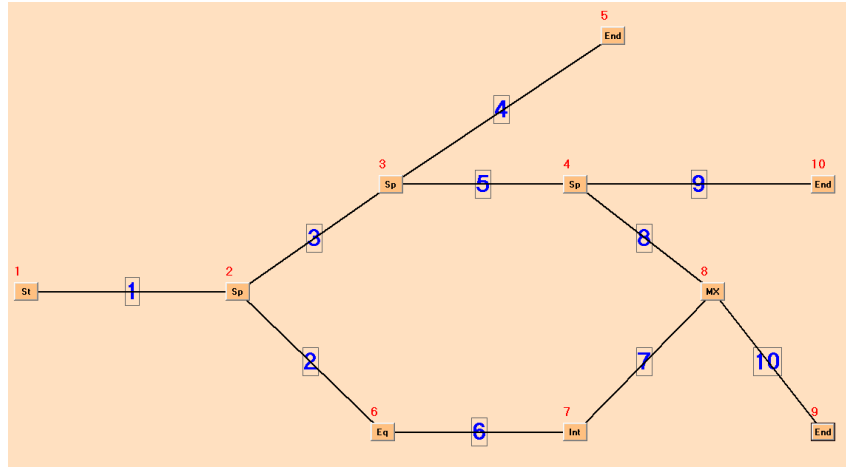
Segment is the second important aspect of a network. A segment is viewed as a pipe section connecting a pair of nodes, one each at its two ends. Its specification such as diameter, surface roughness and length is to be provided by the user. As mentioned earlier, the user will also provide the number 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. The data for each segment is much simpler. User provides the segment length, inner diameter and roughness.
9. 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.



10. 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.
11. 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.
12. 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
13. 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 Design is for off-line usage in design offices and/or technical services of any operating company.

**Table 1: Associated Segment Data for nodes**

<b>Node Number</b>	<b>Node Type</b>	<b>ASN 1</b>	<b>ASN 2</b>	<b>ASN 3</b>
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		

Once the network is coded as per the above instructions, transient network simulation can be carried out.

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 the 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 networks. 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 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.

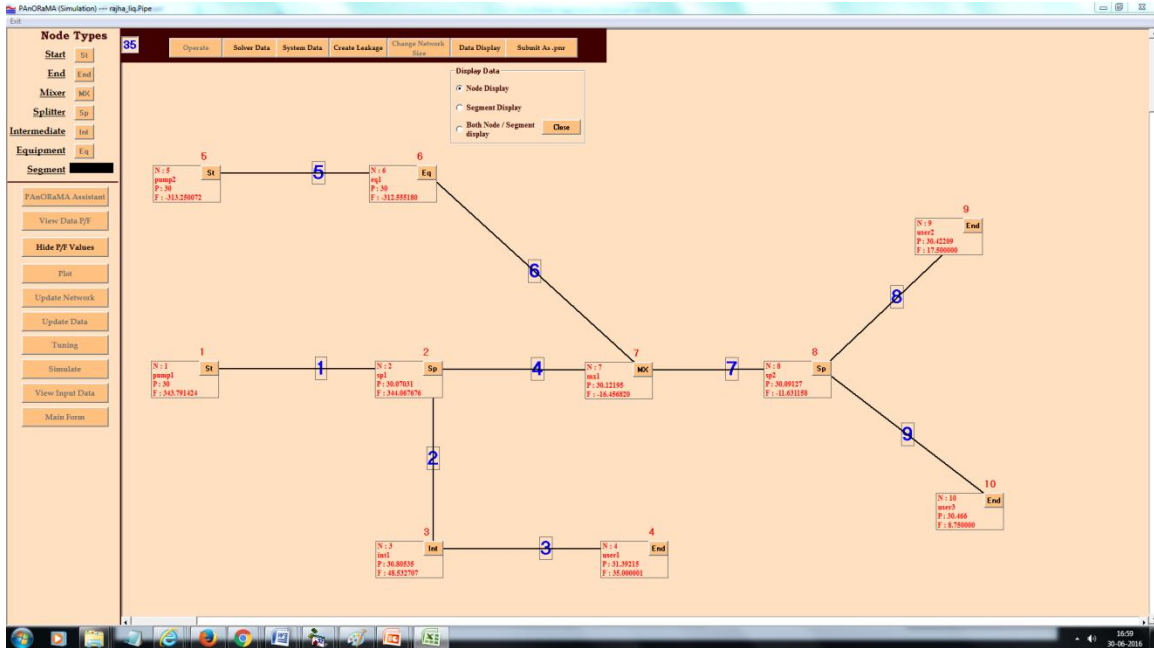


Figure 3a: Live display of node data

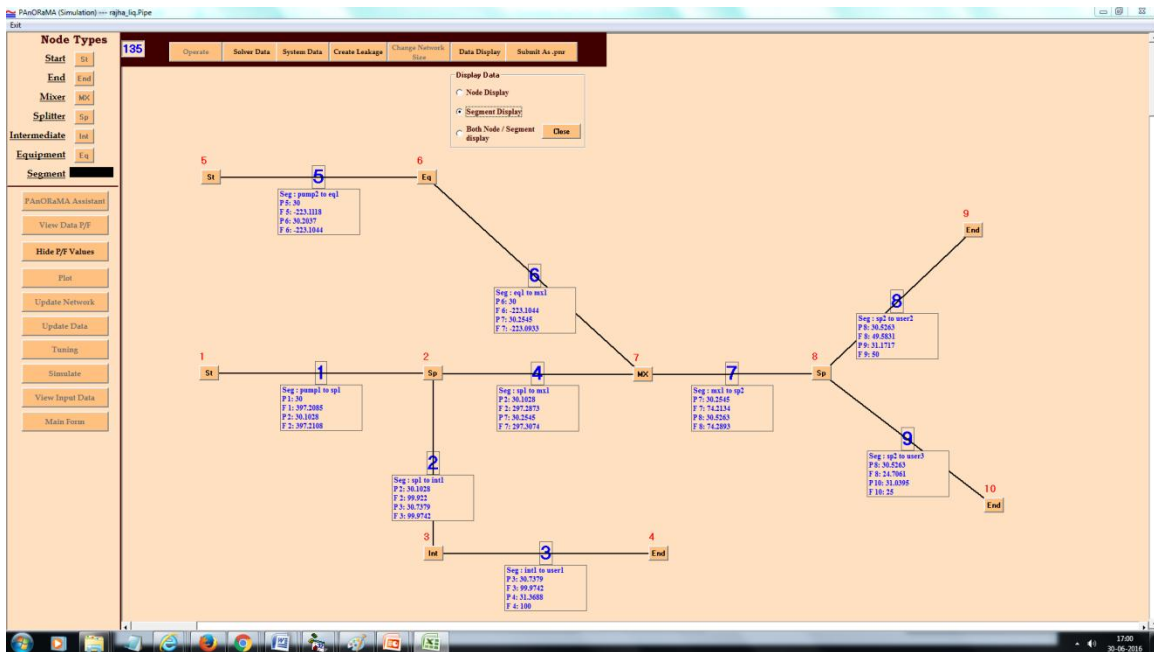
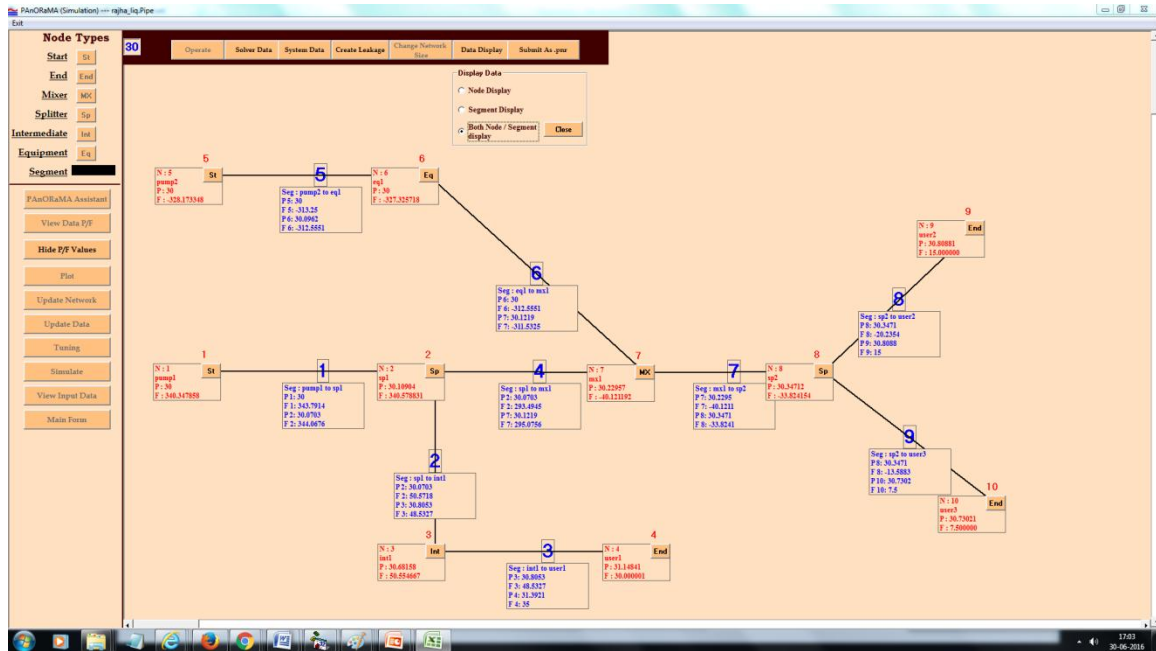


Figure 3b: Live display of Segment data



**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.

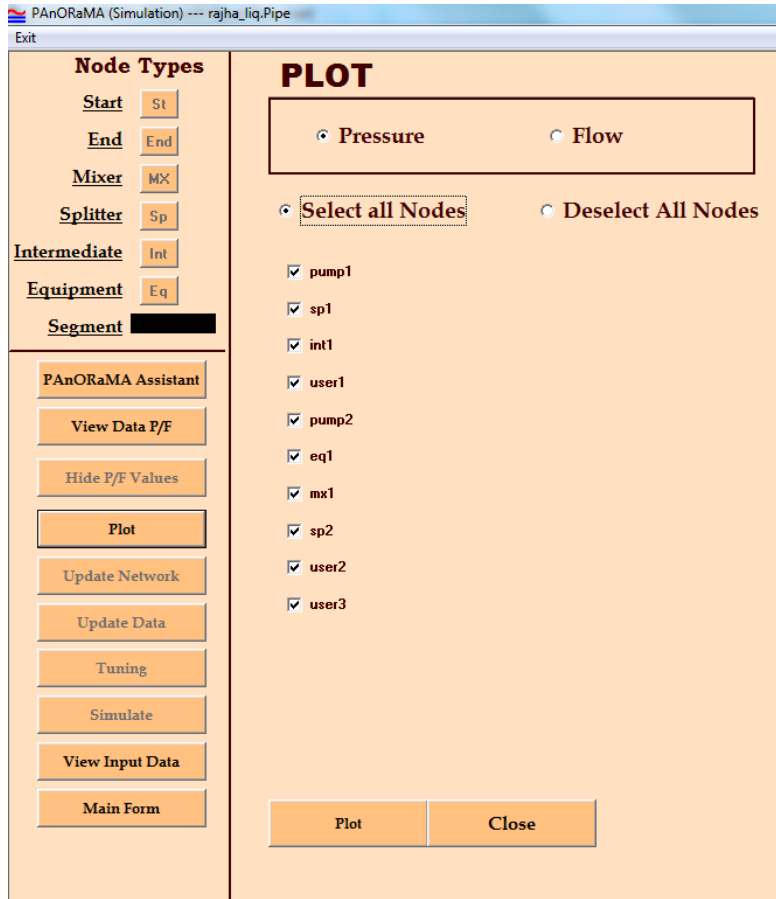


Figure 4a: Selection for Pressure plots

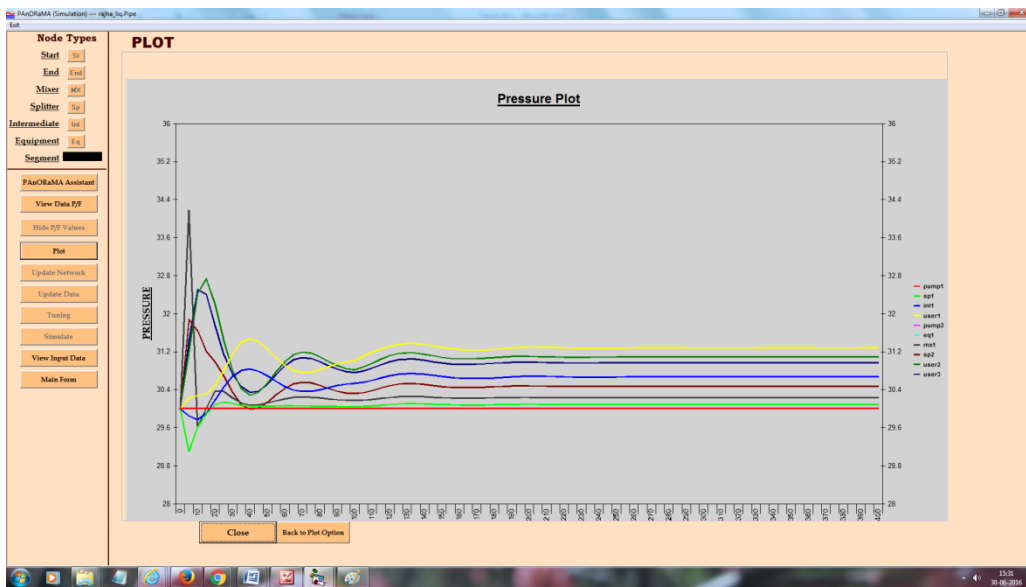


Figure 4b: Graphical display of Pressure plots

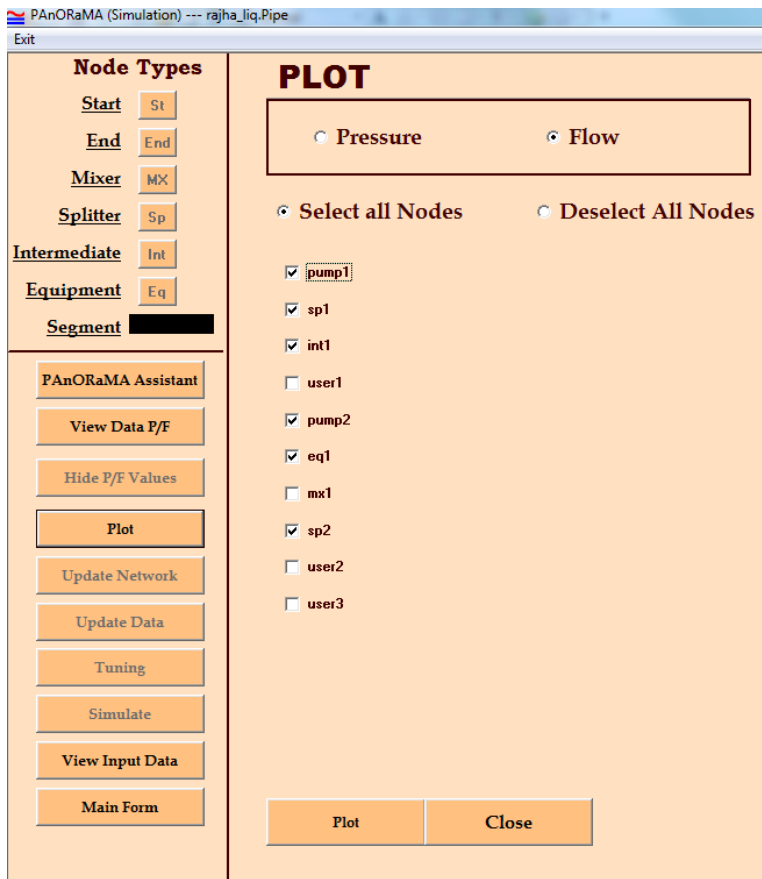
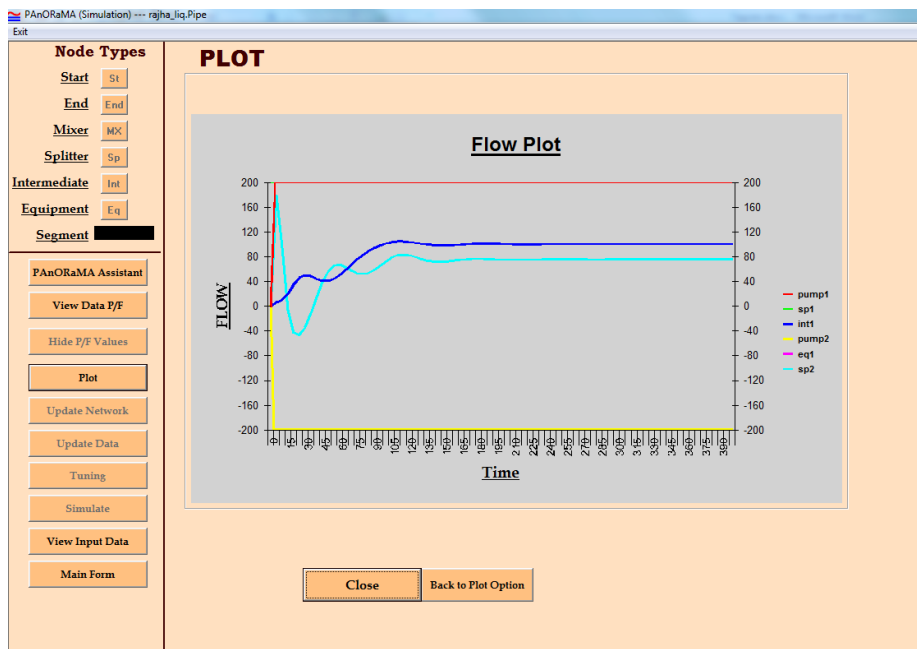
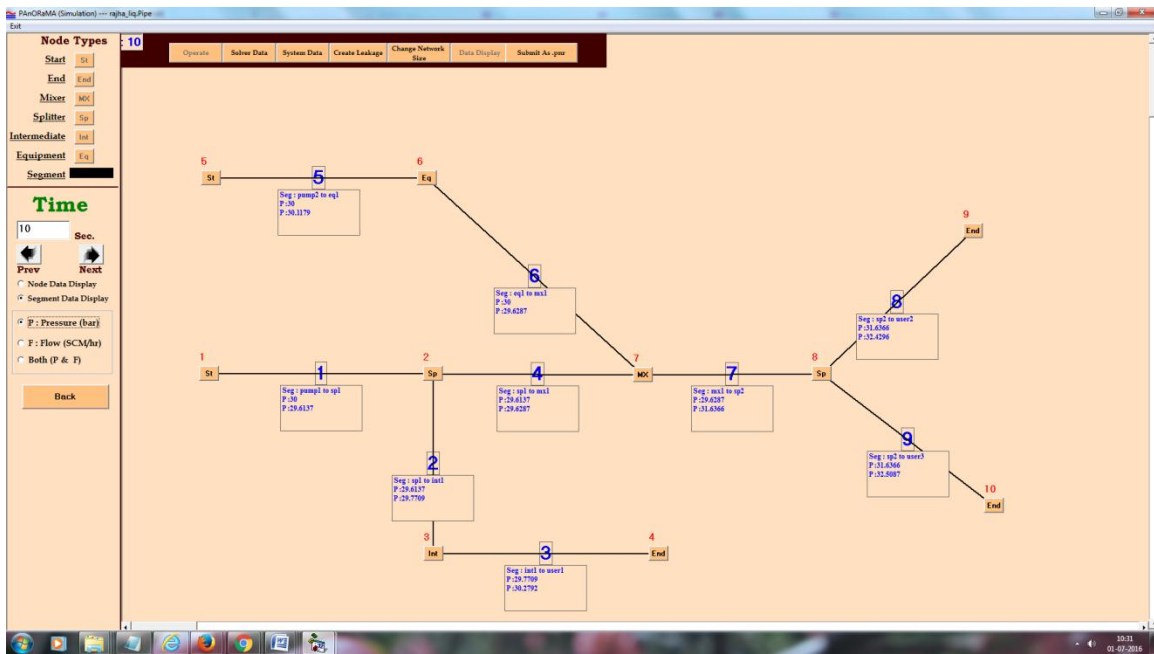


Figure 5a: Selection for Flow plots



**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**

<b>S. No.</b>	<b>Existing Node Type</b>	<b>Possible Changes</b>
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

The application can be used for design of a proposed network as well as rating of an existing network by setting up the simulation and carrying out simulation experiments with it.

Various technical tasks that the transient simulator can support are tabulated in Table 3.

These are all off-line tasks and a desktop version of PAnORaMA will be sufficient for the same.

**Table 3: Technical Tasks supported by PAnORaMA**

<b>Sr. No</b>	<b>Technical Task</b>
1.	Simulation (gas/liquid networks)
2.	Design (Pipe Sizing, pump / compressor rating, Instrument rating and location)
3.	Water hammer and surge analysis
4.	What-if analysis
5.	Simulation support for Forecasting and Scheduling
6.	Network Expansion (incremental)
7.	Commerce (Shrinkage, line pack calculations, billing)

## **CONCLUSION**

The paper discussed a comprehensive transient simulator for flow networks, PAnORaMA. The network, or its simplest form as a dedicated pipeline, can be designed for transporting gas or liquids. The transient simulator can help solve several design tasks such as pipe sizing, pump/compressor rating, water hammer analysis, pressure surge analysis, line pack and shrinkage calculations for cross-country gas transportation networks etc. PAnORaMA Design should serve as a powerful tool for professionals

engaged in design and engineering of process plants, power plants, ships, municipal distribution networks, cross-country transportation of oil, gas and petroleum products etc.