# Hydraulic and Surge Analysis in a Pipeline Network using Pipeline Studio®

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***Abstract*— Pressure surge is a severe problem that causes catastrophic damage to pipelines. Several sequential actions are required to mitigate the pressure surge and protect the pipeline from damage. The present paper investigates the condition at which pressure surge is likely to occur and proposes the methods by which it can be avoided. A hydraulic steady-state simulation and surge analysis is carried out using Pipeline Studio® Liquid version 3.6.0 (PLS) that calculates time-invariant pressure, temperature and flow profile throughout a pipeline network for specified boundary conditions and network element set points. Using the results obtained by steady state simulation as the starting point, the simulation is further carried out for transient conditions. Various pressure trends obtained by exposing the pipeline to various surge occurrence scenarios have been collected and compared with the Maximum Allowable Operating Pressure (MAOP) in pipelines. Result successfully finds out the conditions that causes the formation of pressure surge. Further actions have been recommended that mitigates the formation of pressure surge.**

***Keywords - Surge Analysis, Pipeline studio, Steady state and transient state simulation, mitigating surge, Liquid pipeline hydraulics.***

## I. INTRODUCTION

Pipeline pressure surges are occurred by a sudden increase in pressure which is produced by a change in velocity of the moving fluid in a pipeline. Usually, during pipeline design, the movement of fluid is based on steady state calculations of the static head and frictional head losses, using the maximum operating pressure plus a small safety factor. However, in any system, the flow must be started and stopped by pump or valve operations and these can generate transient pressures well in excess of the steady state pressures. The hydraulic simulation of pressure and flows in fluids caused by the transient operations of the pumps and valves are required to carryout for the pipeline surge analysis studies.

The Pressure surges occur due to the events such as shutting down of a pumping station or pumping unit, unstable controls, oscillation in tank levels, the sudden closure of a valve, or any other sudden blockage of the moving fluid [3]. These pressure surges may occur in all fluid pipeline systems and can result in pipeline fatigue and pipeline failure. The effects of surge may be catastrophic failure of the pipeline system and equipment or fatigue failure of the pipeline supports, instrumentation, equipment and compounds [2].

## II. MECHANISM OF SURGE FORMATION

The rapid closing of a valve or tripping of a pump for example in mid- pipeline, generates two pressure waves, both upstream and downstream of the valve. The upstream wave is high pressure or upsurge wave (rising pressure, falling flow) and the downstream is a low pressure wave (falling pressure, falling flow) [1, 5].

Consider a pipe leading from a reservoir to some unknown destination far downstream. A valve is placed at a distance 'L' from the reservoir. Considering the friction in the line to be negligible, the difference between energy grade line and hydraulic grade line can be neglected since the velocity heads are generally quite small in relation to surge pressure. The flow of liquid at the valve is suddenly stopped when the valve is rapidly closed. Consequently, the pressure head at the valve increases abruptly. The increase in pressure at the valve results in a swelling of the pipe and an increase in the density of the liquid. The amount of pipe stretch and liquid volume decrease depends on the pipe material, size and liquid elasticity [2]. Considering only the upstream of the valve the surge mechanism is shown in the *Fig I.*

1. For t = 0, the pressure profile is steady, which is shown by the pressure head curve running horizontally because of the assumed lack of friction. Under steady-state conditions, the flow velocity is $v_0$.

2. The sudden closure of the valve at the downstream end of the pipeline causes a pulse of high pressure $\Delta h$, and the pipe wall is stretched. The pressure wave generated runs in the direction opposite to the steady-state direction of the flow at

the speed of sound and is accompanied by a reduction of the flow velocity to zero in the high pressure zone. The process takes place in a period of time $0 < t < 1/2\ T_r$, where $T_r$ is the amount of time needed by the pressure wave to travel up and down the entire length of the pipeline. The important parameter $T_r$ is the reflection time of the pipe. It has a value of 2L/a.

3. At $t = 1/2T_r$ the pressure wave has arrived at the reservoir. As the reservoir pressure p is constant, there is an unbalanced condition at this point. The pressure wave is reflected in the opposite direction. The flow velocity changes sign and is now headed in the direction of the reservoir

4. A relief wave with a head of -Δh travels downstream towards the valve and reaches it at a time $t = T_r$. It is accompanied by a change of velocity to the value $-v_0$.

5. Upon arrival at the closed valve, the velocity changes from $-v_0$ to 0. This causes a sudden negative change in pressure of -Δh.

6. The low pressure wave –Δh travels upstream to the reservoir in a time $T_r < t < 3/2T_r$, and at the same time, velocity changes to zero.

7. The reservoir is reached in a time $t = 3/2T_r$ and the pressure becomes equal to the reservoir's pressure head.

8. In a period of time $3/2T_r < t < 2T_r$ , the wave of increased pressure originating from the reservoir runs back to the gate valve and v once again adopts the value $v_0$.

9. At $t = 2T_r$, conditions are exactly the same as at the instant of closure t = 0, and the whole process starts over [5].

The downstream of a rapidly closed valve are also very important since this result in low pressures. This may be sufficient to reduce the absolute pressure below the vapor pressure of the liquid, which results in forming of vapor cavity [5].

## III. MITIGATION PROCEDURES

One should consider surge mitigation as a safety measure while designing a pipeline system. There are many procedures and devices available to mitigate unacceptable pressures [1]. Some of them are;

- ✓ Increasing the valve closure time
- ✓ Providing relief valves
- ✓ Providing surge tanks
- ✓ Increase pipeline diameter
- Increase wall thickness

## IV. PLANNING A SIMULATION

Before creating a pipeline network and running a simulation, you should consider these issues:

- ✓ Network configuration
- ✓ Factors to be analyzed
- ✓ Time period required to complete the simulation
- ✓ System variables to be changed and kind of schedule
- ✓ Constraints required for the pipeline network
- ✓ Steady-state simulation or transient (dynamic) simulation to be run

### *A. Steady state simulation*

A steady-state simulation calculates time-invariant pressure, temperature and flow profiles throughout a pipeline network using specified boundary conditions and network element set points that are entered, i.e. the steady-state run calculates the hydraulic state of a pipeline system operating at equilibrium. This type of simulation can be done to obtain steady-state data or to provide the initial starting conditions for a transient simulation.

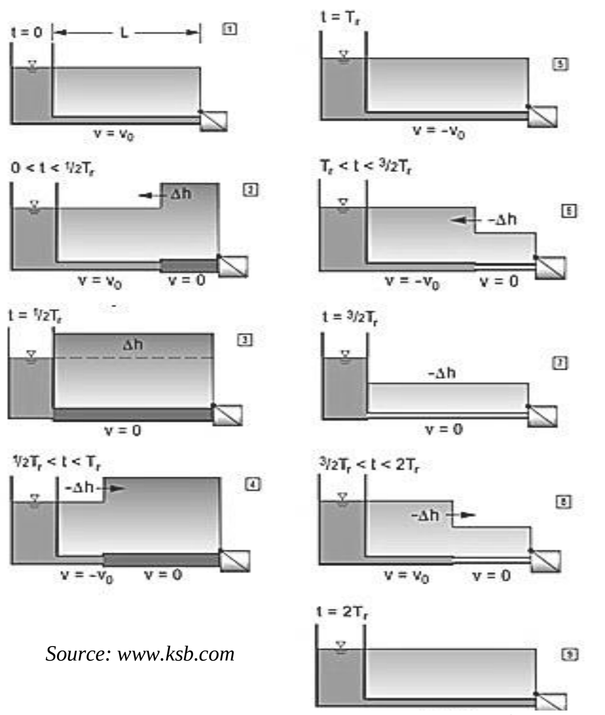
When a steady-state simulation is requested, PLS validates the network, exports a keyword file and runs the steady-state simulation. Steady-state results can be viewed using a variety of formats. For example, one can view results using data blocks (on a network view), a table view, formatted text output reports (the Keyword Processor Report and Steady-State Report) or a profile chart [7].

### *B. Transient simulation*

A successful steady-state simulation can be followed by a transient simulation.

A transient simulation models the dynamic response of the pipeline network to changes in one or more system variables, such as source/delivery rates or network element set-points. Transient calculations are more complex and require more processing time than steady-state calculations. Useful results can be obtained from a transient simulation only if changes occur in one or more of the parameters governing the pipeline network [7].

Various transient simulations are performed using the steady-state results as the starting point. However, certain changes (such as changes in pipe diameter) require the steady-state to be re-run before running a transient simulation. When a request for a transient simulation is made after incorporating such changes, PLS detects the changes and automatically re-runs a steady-state simulation before running the transient simulation [7].



*Source: www.ksb.com*

Fig 1. Pressure and velocity waves in a single-conduit, frictionless pipeline following its sudden closure

## V. CASE STUDY

A case study is carried out using PLS by considering a product pipeline network. The simulation is carried out by considering only the rapid closure of a valve. The following network elements are used:

- ✓ Pipes
- ✓ External Regulators
- ✓ Valves
- ✓ Pumps

### *A. Pipe*

In PLS, a pipe has uniform characteristics along its entire length. Thus, a pipeline is broken into a number of pipes at the points where such characteristics change. A pipe is connected to a node at each of the upstream and downstream ends. The length must be specified for every pipe. For calculation purposes, the simulator subdivides each pipe into smaller intervals. The boundaries between these intervals are called knots and represent the points along pipe at which hydraulic calculations are made. The simulator calculates pressure, density and velocity at every knot.

A pipe is connected to other items in the configuration by an upstream node and a downstream node. Flow from the upstream end to the downstream end of a pipe is reported as positive; flow in the opposite direction is reported as negative. A pipe and a network element should not be connected in parallel (that is, they should not both be attached to the same upstream and downstream node). A pipe and a network element can be connected to the same upstream or downstream node, but not both.

### *B. External Regulators*

An external regulator is a device which models flow into or out of a pipeline network at a node. In PLS, one can include external regulators in a pipeline network that represent supplies and deliveries. An external regulator is always connected to just one node.

*1) Supply:* Supply points are locations where a source of fluid enters a pipeline network configuration. A supply external regulator allows you to specify the fluid properties and temperature of the flow entering the system. At least one constraint must be defined for a supply external regulator. The recommended constraints are either maximum inlet pressure or maximum inlet flow rate.

*2) Delivery:* Delivery points are locations where fluids leave a pipeline network, that is, the fluids are delivered to points outside the simulated system. At least one constraint must be specified for a delivery external regulator. The recommended constraints are either minimum delivery pressure or maximum delivery flow rate.

### *C. Valves*

The Valves used for the case study are

- ✓ Block Valve
- ✓ Relief Valve

*1) Block Valve:* A block valve, as defined by PLS is a device that provides a variable resistance to flow based on the percent open value. A block valve is attached to other network elements or pipes by its upstream and downstream nodes. When fully open, a block valve provides some amount of resistance to flow through the valve (which may be in either direction). When closed, the flow is assumed to be zero and the upstream and downstream flows are assumed to be independent of each other. When placing fully-closed block valves into a pipeline network, one should be careful to avoid creating pressure-unspecified networks. For block valves, there is only one mode of control: Percent Open. A block valve cannot be placed in tight parallel with another network element.

*2) Relief Valve:* A relief valve, as defined by the PLS, is a device that is used to control or limit the pressure in a system which can build up by upset, instrument or equipment failure. The relief valve is designed or set to open at a predetermined set pressure to protect the pipe and equipment from being subjected to pressures that exceed their design limits.

The valve has been designed to comply with API 520 part 1, Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries. Two valve types are available, the “pop” type and the “pilot” type.

The “pop” type valve opens to 100% open as soon as the cracking pressure is reached, and closes when the line pressure falls to the closure pressure. The “pilot” type valve starts to open when the cracking pressure is reached, and follows the CV curve of the valve tending toward fully open based on the overpressure value. The valves closure tends toward the close pressure value based on the falling line pressure, the overpressure value and the close pressure value. The relief valve is a two node device. This means that a pressure and/or flow controlling device or network is required on the downstream side of the valve. For a liquid pipeline configuration this may be an external regulator, such as a delivery or leak delivery, or a nozzle and tank arrangement. Downstream pipework may also be included [7].

### *D. Pump*

The pump used in this case is a centrifugal pump. A centrifugal pump, as defined by the PLS, is a device which employs a rotating impeller to move the liquid. The behavior of a centrifugal pump is characterized by a relationship between the flow through the pump and the differential head produced by the pump. A centrifugal performance curve (CPID) is created by entering head curve and efficiency curve data.

The required (shaft) power for a pump is the total power needed to drive the pump i.e. the hydraulic power required to move the liquid modified by the mechanical efficiency of the shaft plus any additional load on the same shaft. When specifying a maximum power constraint on a pump it is the shaft power that is constrained.

A pump is connected to other items in the configuration by an upstream node and a downstream node. Flow through a pump from the upstream node towards the downstream node is reported as positive; flow in the other direction is reported as negative.

## VI. METHODOLOGY

The Methodology adopted to solve the case study is as shown in *Fig 2*.

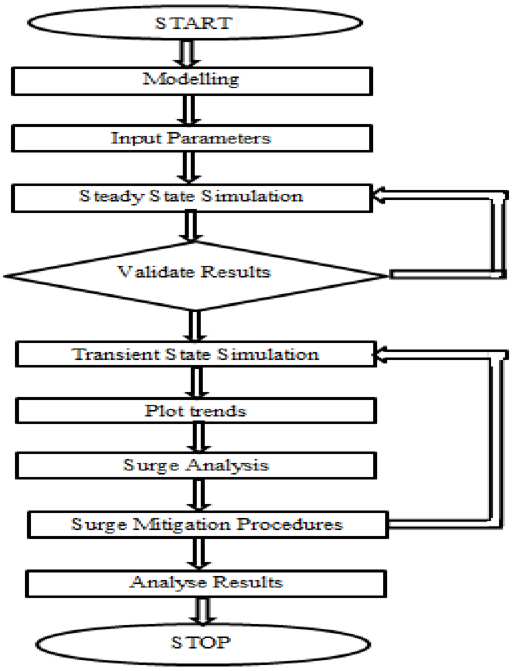



Fig 1. Flow diagram to solve the case study

## VII. MODELLING THE NETWORK

A pipeline network is a visual representation of a pipeline system that is to be modeled. The pipeline system can be a real-world system, where modifications are to be made to improve its operation, or a planned pipeline system. A pipeline network can be created in PLS using a network view or a drawing area on which various symbols, representing actual equipment and pipes, can be added.

The pipeline used in the case study is 1036.4 Km (643.989 mi) long from A to G as shown in *Fig 3*, with A as the originating station, three intermediate tap-off stations at C, E&F and a main delivery station at G. The intermediate tap-off points at C&E are marked as special marketing zones, which are used according to the demand, kept idle in this case. The network consists of six block valves and seven centrifugal pumps.

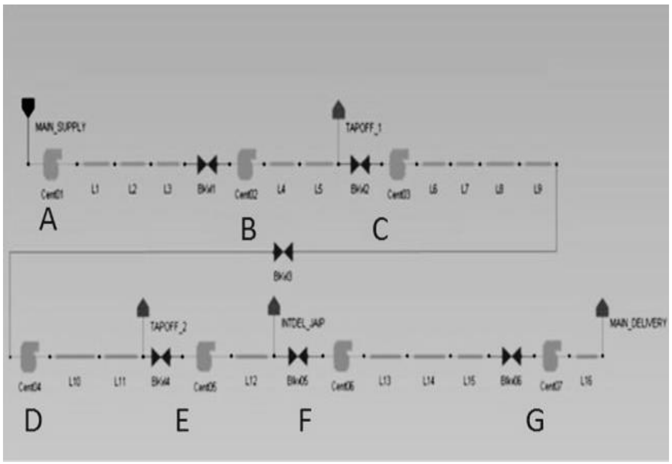



Fig 2. A product pipeline network modelling using pipeline studio®

## VIII. CONSIDERATIONS

(a=absolute, g= gauge)

- ✓ The pipe grade is considered as API 5L X-65
- ✓ Yield stress of the pipes are 4588.72 kg/cm$^2$ a
- ✓ Yield factor of safety is taken as 0.72
- ✓ Roughness of all pipelines is considered as 45 microns
- ✓ Thermal expansion coefficient is taken as 1.16E-05/$^0$C
- ✓ Young's Modulus is considered as 2110810 kg/cm$^2$ a
- ✓ Maximum pressure at main supply is taken as 80 kg/cm$^2$ g
- ✓ Minimum pressure at main delivery is taken as 6 kg/cm$^2$ g
- ✓ Maximum flow at intermediate delivery (F) is 71 m$^3$/h
- ✓ Fluid temperature is taken as 30 $^0$C
- ✓ Colebrook-White friction factor equation is used for calculating the pressure drop in the pipeline.
- ✓ The pumps are in running state for 1 hour even after closing the valve.
- ✓ Time taken to fully open the block valve is 30 sec.
- ✓ All the input parameters for the case study are shown in *Table I, II, III, IV, V, and VI*, which can be found in appendices.

## IX. VALIDATION AND SIMULATION

General steps to run a simulation

- ✓ Run a steady-state simulation to get a steady-state result.
- ✓ Run a transient simulation to get a dynamic result.
- ✓ (Optional) Run a transient re-start from the last transient simulation state.
- ✓ (Optional) Run an interactive transient.

Validation of a pipeline network before running a simulation can also be carried out using PLS. If the validation process encounters more than the maximum number of errors or warnings, then the iteration halts. If any fix is present for such errors or warnings, PLS will indicate the same and select the corresponding network element or pipe where the error is present.

## X. SURGE ANALYSIS CASES

CASE 1: Opening all the valves (Steady State simulation)
CASE 2: Closure of valve Bkvl1 at Location B.
CASE 3: Closure of valve Bkvl2 at Location C
CASE 4: Closure of valve Bkvl3 at Location D
CASE 5: Closure of valve Bkv4 at Location E
CASE 6: Closure of valve Bkvl5 at Location F
CASE 7: Closure of valve Bkvl6 at Location G

## XI. RESULTS AND OBSERVATIONS

After running case 1 simulation i.e. steady state the profiles shown in *Fig 4, Fig 5, Fig 6* are obtained.

The steady state results are used for running the transient simulation. A time scenario is created for all the block valves to close suddenly. The time assumed is 30 sec. The scenario conditions can be seen in *Table VII*.

The transient simulation for all other cases is run in sequence. The maximum pressures obtained at the block valves are shown in *Table VIII*. Here the upstream pressures of block valve are very high since the pump is not stopped for one hour even after the valves closure, based on the assumption made. The surge formation is considered when the pressure exceeds 110% of the MAOP.

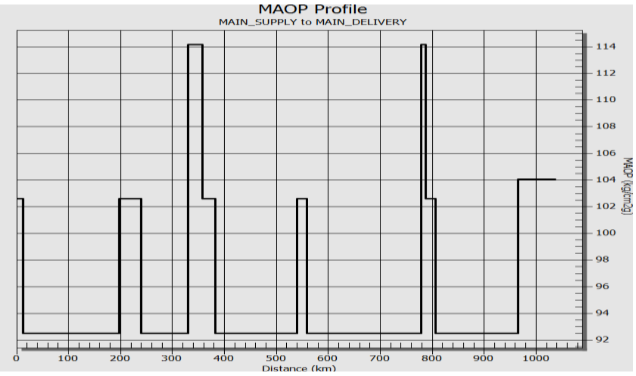



Fig 3. MAOP profile for whole pipeline network

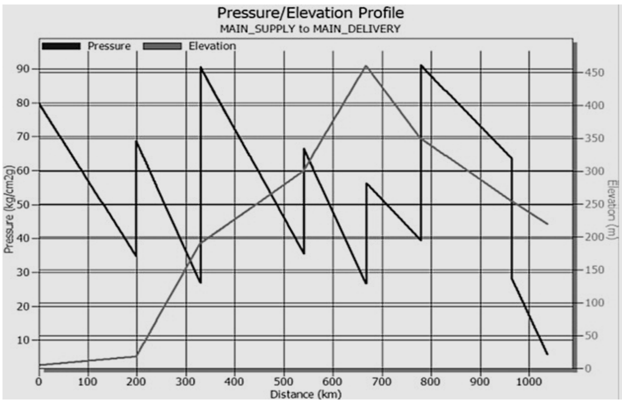



Fig 4. Pressure/elevation profile for whole pipeline

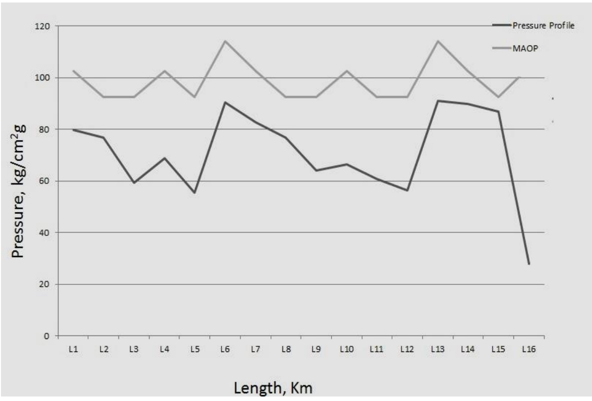



Fig 5. MAOP and Pressure Profile for whole pipeline

## XII. MITIGATION PROCEDURES

In this case study we adopted two mitigation procedures 1) Increase the valve closure time and 2) Provide surge relief valve at the upstream of the block valve.

### *A. Mitigation Procedure 1: Increase the valve closure time.*

The valve closure time is increased from initial 30 sec to 120 sec. The transient simulation is run once again. The surge formation time after gradual closure of valve is verified with the initial surge formation conditions with sudden closure of valve. The scenario table for all the block valves after increasing the closure timing is shown in *Table IX*.

From *Fig 7* it is observed that the time difference to form surge for gradual and sudden closure of valve is very minimum. The values can be found in *Table X*. In real practice this time does not have any effect in mitigating the surge.

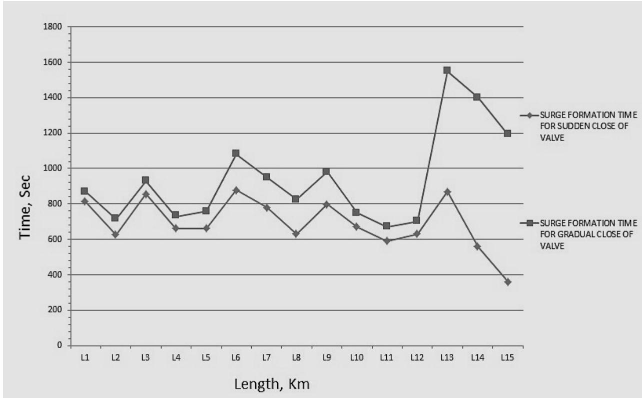



Fig 6. Comparison of time for surge formation

### B. *Mitigation Procedure 2: Provide Relief Valve at upstream of the block valves.*

A relief valve is placed at the upstream of the block valves at all the locations (referring to *Fig 8*). A set point is maintained so that whenever the pressure reaches the set point, the relief valve activates and reduces the pressure.

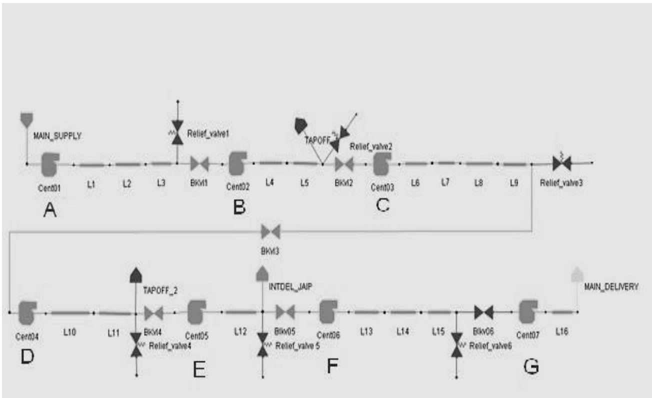



Fig 7. Relief valve placed at upstream of the block valve at all locations

The Results from *Table XI* shows that after placing the relief valve, the surge is completely eliminated.

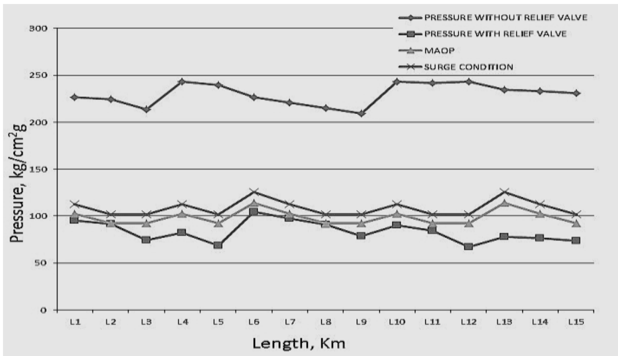



Fig 8. Pressures with and without relief valves

## XIII. CONCLUSIONS

This paper explains the mechanism of surge formation in liquid pipelines and provides a brief idea of Pipeline Studio® Liquid version 3.6.0; its elements, input parameters required to run a surge analysis, validating results and applying mitigation procedures. The case solved in this paper shows two methods to mitigate the surge, either by increasing the valve closure, which does not have any effect on mitigating surge in this case or by providing relief valve at all the locations which successfully mitigates the surge formation. However, the relief valve has got some disadvantages like high cost, maintenance, etc. This case can also be solved with other mitigation procedures like increasing the wall thickness, increasing pipe diameter or even providing surge tanks, which can be the basis for future work.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Hanmer, G., Bachman, S., & Lind, G. (2014, May 13). Pipeline Surge Analysis Studies. Pipeline Simulation Interest Group
[2] Watters, Gary Z. (1984) Analysis and control of unsteady flow in pipelines. Boston: Butterworths.
[3] Introduction to pressure surge in liquid Systems, GBHE-PEG-FLO-305, Process Engineering Guide- www.GBHenterprises.com
[4] M. Luskin (Volume 16, No. 1, February, 1979). "An Approximate Procedure for Nonsymmetric, Nonlinear Hyperbolic Systems with Integral Boundary Conditions". Siam Journal on Numerical Analysis.
[5] Horst-Joachim Lüdecke. & Bernd Kothe (volume 01, Brochure, 2006). KSB Know –how Water Hammer. www.ksb.com
[6] www.energy-solutions.com/products/pipelinestudio
[7] Pipeline Studio 3.6.0, release notes -www.energy-solutions.com

## APPENDICES

## TABLES

TABLE I PIPELINE INPUT PARAMETERS

| S.no | Pipe name | Length | Line size | Wall thickness | Knot space |
|---|---|---|---|---|---|
| Units | | km | in | mm | km |
| 1 | L1 | 13 | 18 | 7.1 | 0.5 |
| 2 | L2 | 77 | 18 | 6.4 | 1.0 |
| 3 | L3 | 108 | 18 | 6.4 | 1.5 |
| 4 | L4 | 42 | 18 | 7.1 | 1.0 |
| 5 | L5 | 89.5 | 18 | 6.4 | 1.5 |
| 6 | L6 | 28.7 | 18 | 7.9 | 0.5 |
| 7 | L7 | 23.5 | 18 | 7.1 | 0.5 |
| 8 | L8 | 48.3 | 18 | 6.4 | 1.0 |
| 9 | L9 | 109.9 | 18 | 6.4 | 1.5 |
| 10 | L10 | 18.6 | 18 | 7.1 | 0.5 |
| 11 | L11 | 109 | 18 | 6.4 | 1.5 |
| 12 | L12 | 111.5 | 18 | 6.4 | 1.5 |
| 13 | L13 | 8.2 | 18 | 7.9 | 0.5 |
| 14 | L14 | 19.1 | 18 | 7.1 | 0.5 |
| 15 | L15 | 158.8 | 18 | 6.4 | 1.5 |
| 16 | L16 | 71.3 | 16 | 6.4 | 1.0 |

TABLE II VALVE INPUT PARAMETERS

| S.no | Name | CV | %open | Size | Location |
|---|---|---|---|---|---|
| Units | | | Percent | in | |
| 1 | BKvl1 | 5000 | 100 | 18 | B |
| 2 | Bkvl2 | 5000 | 100 | 18 | C |
| 3 | Bkvl3 | 5000 | 100 | 18 | D |
| 4 | Bkvl4 | 5000 | 100 | 18 | E |
| 5 | Bkvl5 | 5000 | 100 | 18 | F |
| 6 | Bkvl6 | 5000 | 100 | 18 | G |

TABLE III ELEVATION DATA

| S.no | Mile post | Elevation |
|---|---|---|
| 1 | 0 | 4.8 |
| 2 | 198 | 18 |
| 3 | 329 | 190 |
| 4 | 539 | 300 |
| 5 | 667 | 460 |
| 6 | 778 | 350 |
| 7 | 965 | 254 |
| 8 | 1036 | 220 |

TABLE IV PUMP INPUT PARAMETERS

| S.no | Name | Max flow | Min up pressure | Check | Free flow | Location |
|---|---|---|---|---|---|---|
| Units | | $m^3/h$ | $kg/cm^2$ g | | | |
| 1 | Cent01 | 784 | - | Yes | No | A |
| 2 | Cent02 | - | 34.81 | Yes | No | B |
| 3 | Cent03 | - | 27.00 | Yes | No | C |
| 4 | Cent04 | - | 35.60 | Yes | No | D |
| 5 | Cent05 | - | 26.74 | Yes | No | E |
| 6 | Cent06 | - | 39.50 | Yes | No | F |
| 7 | Cent07 | - | 63.58 | Yes | No | G |

TABLE V FLUID PARAMETERS

| Parameter | Units | |
|---|---|---|
| Name | | MS |
| Class | | Crude |
| Density lower range | $kg/m^3$ | 740 |
| Density upper range | $kg/m^3$ | 720 |
| Pressure lower range | $kg/cm^2g$ | 2 |
| Pressure upper range | $kg/cm^2g$ | 100 |
| Temp lower range | $^0C$ | 2 |
| Temp upper range | $^0C$ | 55 |
| Thermal conductivity | W/m-K | 0.1385 |

TABLE VI RELIEF VALVE PARAMETERS

| Name | Rel_ Valve 1 | Rel_ valve 2 | Rel_ valve 3 | Rel_ valve 4 | Rel_ valve 5 | Rel_ valve 6 |
|---|---|---|---|---|---|---|
| **Open pressure** | 50 | 40 | 40 | 50 | 50 | 50 |
| **Clos pressure** | 50 | 40 | 40 | 50 | 50 | 50 |
| **Over pressure** | 90 | 80 | 80 | 90 | 90 | 90 |
| **Pressure dashboard** | 10 | 10 | 10 | 10 | 10 | 10 |
| **Type of Valve** :Pilot<br>**Coef. of Discharge :** 100000<br>**Equivalent Diameter :** 18 | | | | | | |

TABLE VII SCENARIO TABLE FOR BLOCK VALVES FROM CASE 2 ONWARDS

| Name | Bkvl1 | Bkvl2 | Bkvl3 | Bkvl4 | Bkvl5 | Bkvl6 |
|---|---|---|---|---|---|---|
| **Initial condition** | open | open | open | open | open | open |
| **10 sec** | 100 | 100 | 100 | 100 | 100 | 100 |
| **20 sec** | - | - | - | - | - | - |
| **30 sec** | - | - | - | - | - | - |
| **40 sec** | 0 | 0 | 0 | 0 | 0 | 0 |
| **60 sec** | 0 | 0 | 0 | 0 | 0 | 0 |
| **3600 sec** | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE VIII OBSERVATIONS FROM ALL THE CASES

| Case | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 |
|---|---|---|---|---|---|---|---|
| **Valve closure time** | - | 30 | 30 | 30 | 30 | 30 | 30 |
| **Element name** | - | Bkvl1 | Bkvl2 | Bkvl3 | Bkvl4 | Bkvl5 | Bkl6 |
| **Element location** | - | B | C | D | E | F | G |
| **Pipes effected** | - | L1, L2, L3 | L4, L5 | L6, L7, L8, L9 | L10, L11 | L12 | L13, L14, L15 |
| **Max upstream pressure** | - | 211.3 | 231.6 | 202.5 | 231.8 | 243.0 | 229.5 |
| **Max downstrea m pressure** | - | 34.81 | 27.00 | 35.60 | 26.74 | 39.50 | 63.58 |
| **Time to reach surge condition (110% MAOP)** | - | 627 | 660 | 630 | 590 | 630 | 360 |

TABLE IX SCENARIO TABLE FOR GRADUAL CLOSURE OF VALVE

| Name | Bkvl1 | Bkvl2 | Bkvl3 | Bkvl4 | Bkvl5 | Bkvl6 |
|---|---|---|---|---|---|---|
| **Initial condition** | open | open | open | open | open | open |
| **10 sec** | 100 | 100 | 100 | 100 | 100 | 100 |
| **20 sec** | 90 | 90 | 90 | 90 | 90 | 90 |
| **30 sec** | 80 | 80 | 80 | 80 | 80 | 80 |
| **40 sec** | 70 | 70 | 70 | 70 | 70 | 70 |
| **50 sec** | 60 | 60 | 60 | 60 | 60 | 60 |
| **60 sec** | 50 | 50 | 50 | 50 | 50 | 50 |
| **70 sec** | 40 | 40 | 40 | 40 | 40 | 40 |
| **80 sec** | 30 | 30 | 30 | 30 | 30 | 30 |
| **90 sec** | 20 | 20 | 20 | 20 | 20 | 20 |
| **100 sec** | 10 | 10 | 10 | 10 | 10 | 10 |
| **130 sec** | 0 | 0 | 0 | 0 | 0 | 0 |
| **3600 sec** | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE X COMPARISON OF TIME FOR SURGE FORMATION

| Pipe | Surge formation time for sudden close of valve | Surge formation time for gradual close of valve |
|---|---|---|
| **Units** | **Sec** | **Sec** |
| L1 | 814 | 870 |
| L2 | 627 | 715 |
| L3 | 855 | 930 |
| L4 | 660 | 730 |
| L5 | 660 | 760 |
| L6 | 880 | 1080 |
| L7 | 780 | 950 |
| L8 | 630 | 825 |
| L9 | 800 | 980 |
| L10 | 670 | 750 |
| L11 | 590 | 670 |
| L12 | 630 | 700 |
| L13 | 870 | 1550 |
| L14 | 560 | 1400 |
| L15 | 360 | 1190 |

TABLE XI COMPARISON OF PRESSURES WITH AND WITHOUT RELIEF VALVE

| Pipe | Pressure without relief valve | Pressure with relief valve | MAOP | Surge condition (110% MAOP) |
|---|---|---|---|---|
| **Unit** | **$kg/cm^2g$** | **$kg/cm^2g$** | **$kg/cm^2g$** | **$kg/cm^2g$** |
| L1 | 226.4001 | 95.02202 | 102.6142 | 112.8756 |
| L2 | 224.3224 | 92.03238 | 92.49709 | 101.7468 |
| L3 | 213.5199 | 74.69753 | 92.49685 | 101.7465 |
| L4 | 243.088 | 82.1295 | 102.6139 | 112.8753 |
| L5 | 239.527 | 68.6868 | 92.49703 | 101.7467 |
| L6 | 226.8748 | 104.9791 | 114.1761 | 125.5937 |
| L7 | 220.6495 | 97.34953 | 102.614 | 112.8754 |
| L8 | 215.2653 | 91.20115 | 92.49709 | 101.7468 |
| L9 | 209.4328 | 78.74358 | 92.49709 | 101.7468 |
| L10 | 243.088 | 90.15495 | 102.614 | 112.8754 |
| L11 | 241.4501 | 84.2947 | 92.49703 | 101.7467 |
| L12 | 243.088 | 67.10762 | 92.49685 | 101.7465 |
| L13 | 234.3168 | 77.86022 | 114.1761 | 125.5937 |
| L14 | 233.1483 | 76.60249 | 102.614 | 112.8754 |
| L15 | 230.9375 | 73.74015 | 92.49709 | 101.7468 |