# Modeling and Field Verification Study of Air Slam Conditions on kalanit Pipeline System

**By Yiftach Brunner & Sathish Kumar**

Air valves are integral part of long water transmission mains and are essential for removal of bulk and residual air during initial and subsequent filling operations. Air valves are also becoming increasingly popular as part of transmission main surge protection system. Whether air valves are considered as part of surge protection system or not during design stage of a transmission main, they may get activated during certain transient events allowing air into the transmission main. While allowing air into the pipeline system may help minimize extreme negative pressure conditions, uncontrolled release of air can lead to air slam conditions and the associated sharp increases in surge pressures. This paper presents a case study on a water transmission main that has experienced several damages along the pipeline system due to uncontrolled release of air during pump trip conditions. Preliminary modeling studies incorporating all existing air valves (kinetic air/vaccum valves) on the transmission main model during a pump trip event revealed the potential for dangerously high surge pressures at several different locations along the transmission main. The models also helped identify critical air valves and the potential for substantial reduction in surge pressures when valves at those locations were replaced by either non-slam air valves with low switching pressures or a new breed of dynamic air valves that eliminate the uncertainty on switching of large orifice to smaller orifice associated with conventional non-slam air valves. Subsequently, extensive field measurements were conducted with three different types of air valves; ordinary kinetic air valves, conventional non-slam air valves and the dynamic air valves at critical locations on the transmission main. High speed (1000Hz) pressure logging devices were able to accurately capture the air slam pressures that resulted from ordinary kinetic air valves on the transmission main. Controlled release of air through dynamic air valves completely eliminated air slam conditions and the associated field measurements were similar to those predicted by mathematical models.

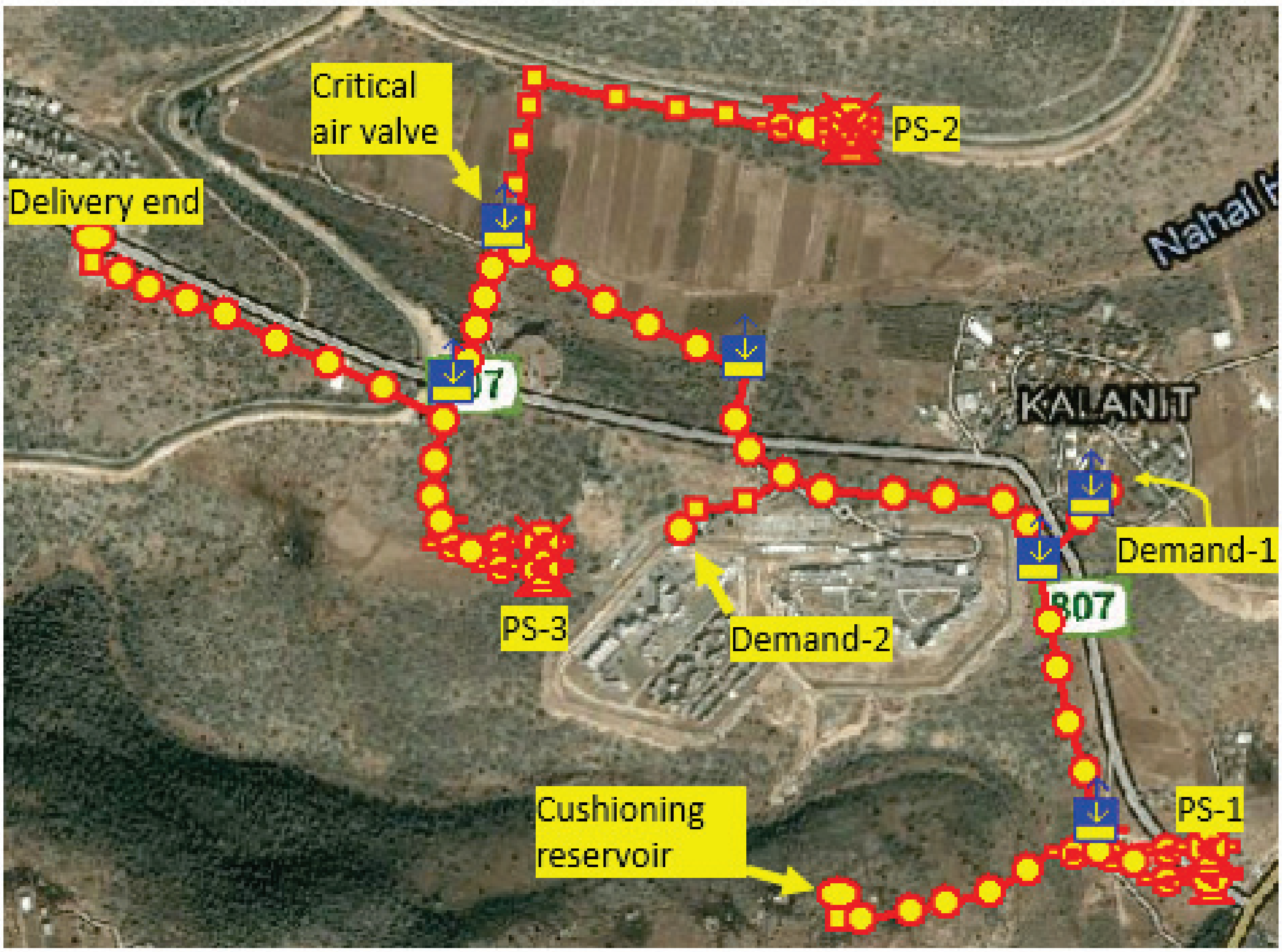



*Figure 1. Overview of Kalanit Pipeline System*

**System Description.** Kalanit Pipeline System (KPS) is a groundwater collection system, pumping water from three different deep well pump stations to a common reservoir that serves the drinking water needs of large settlements near Sea of Galilea, Israel (Figure 1). There are direct tappings on KPS for supply of drinking water to two different settlements along the way. KPS is owned and operated by the Israeli National Water Company "Mekorot" and comprises 12 km of ductile iron and covered steel pipeline ranging from 250mm to 800mm diameters. Ground levels vary from 45m below sea level (-45m) near pump station to 66m above sea level (+66m) at delivery end. Figure 2 shows general arrangement of pumps and associated valves at typical deep well pump stations on KPS.

There was no explicit surge protection on KPS except for the ordinary kinetic air valves that are essential for normal operation of pipeline. KPS has experienced repeated damages at several locations along the pipeline and over a period of time and most of the incidents were associated with the pump trip condition at pump station 1 (PS-1). In particular, repeated damages occurred at the air valve marked as critical air valve on Figure 1.

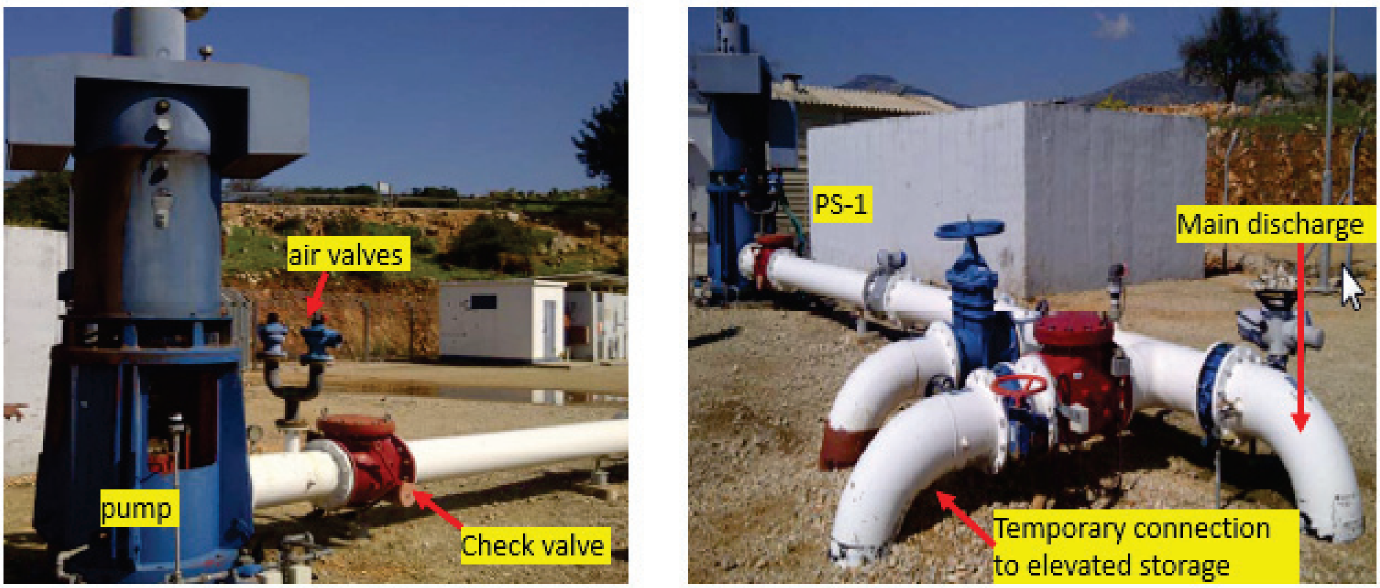



*Figure 2. General arrangement at pump station PS-1*

Attempts were made to provide additional surge protection by way of a connection to a nearby existing elevated storage reservoir (mimicking a one-way surge tank connection). The storage tank is located at an elevation of +43m about 2km from pump station PS-1 and received water from other pumps located within PS-1 area through a 500mm pipeline. Temporary arrangements were made to connect this storage reservoir to the delivery side of PS-1 pumps through a check valve so the potential for extreme negative pressure conditions at pump discharge could be reduced following the pump trip event. Though this arrangement has helped reduce the severity of pressure surges at critical locations, damages to the pipeline system continued.

Since all the air valves on KPS were ordinary kinetic air valves with 100mm nominal inflow and outflow orifices (along with an automatic air release valve for removing residual air), it was suspected that air slam could be the reason for repeated damages to the pipeline systems and a comprehensive modeling study was undertaken.

## Air Valve Characteristics.

***Kinetic air valves**:* Kinetic air valves are air valves that come with a mechanism to prevent premature closure of air valves. An air valve is said to close prematurely when it closes (float lifts up and outflow of air becomes zero) before all bulk air is removed from pipeline surrounding the air valve. Kinetic air valves are used routinely for filling operation on long pipelines. Though air valves that are meant for filling operation can theoretically have one way orifice (flow out of pipeline only), most air valves come with a single orifice that lets flow into and out of the pipeline.

***Automatic air valves**:* Air valves that are meant for removing residual air are generally referred to as automatic air valves. Orifice area of automatic air valves would be negligibly small (usually range from 1-100 $mm^2$) compared to air valve orifices meant for removal of bulk air (e.g. during filling operation) or those meant for protecting the pipelines from extreme negative pressures. Automatic air valves are therefore not considered as part of surge protection system and are ignored for transient analysis.

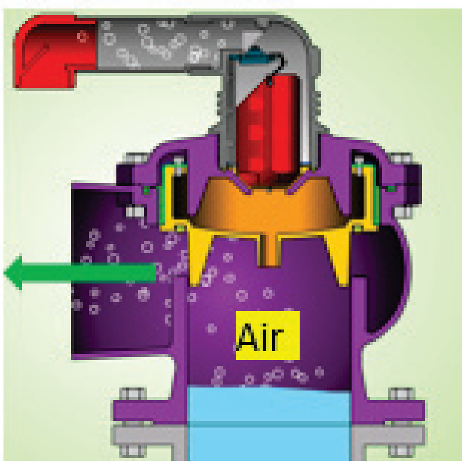
***Combination air valves**:* Air valves that provide both bulk air removal and residual air removal capability are referred to as combination air valves.

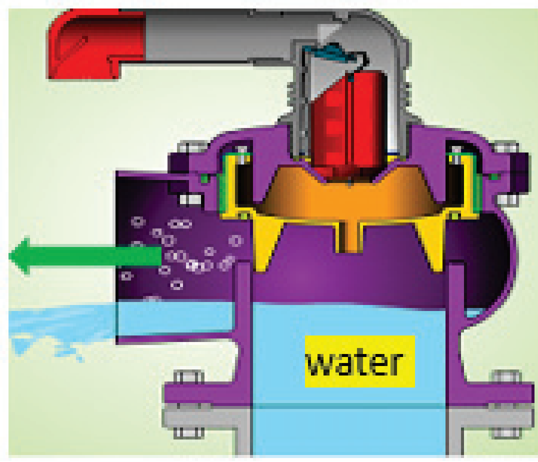
***Non-slam air valves**:* Rapid deceleration of water column results in sharp increase in pressure. Behind every column of air moving out of an air valve, there will be a water column that will be moving with velocities similar to that of air column. Most air valves are designed to prevent spillage of water and close almost instantaneously after all bulk air is vented out. Consequently, the water column behind the air column decelerates abruptly giving rise to rapid increase in pressure. This phenomenon is referred to as air slam condition and the increase in pressure associated with this condition as air slam pressure. The magnitude of pressure wave generated by an air slam condition depends on the velocity of water column just before all air is out of pipeline. Since the velocity of water column depends on the rate at which air is being released out of the air valve, reducing air flowrate will reduce the magnitude of air slam pressure.

One way to accomplish this is to reduce the air valve size. However, this might affect the ability of air valves to protect the pipeline from extreme negative pressure conditions when the air valve is used as surge protection device. Many manufacturers were able to overcome this by providing a check valve type arrangement on the air valve that reduces the area of orifice during venting operation but keeping large area for inflow operation. Air valves with reduced effective outflow area in relation to effective inflow area are referred to as non-slam air valves (Lingireddy et. al., 2004). While such arrangements can reduce the magnitude of air slam pressures they also keep the air in pipelines for longer times which may interfere with pipeline operation.

The last decade has witnessed proliferation of air valves that are capable of removing bulk of the air through a large orifice and switch to a smaller orifice before all air is out of pipeline. Air flow velocity reduces when the switch to a smaller orifice occurs consequently reducing the velocity of water column behind the air column. Smaller water column velocities would result in smaller air slam pressure that occurs when all air is out of the pipeline. These types of non-slam air valves are quite popular as surge protection devices on potable water systems and are referred to as three-stage air valves.

***Dynamic air valves****:* While non-slam air valves reduce the speed of water column just before all air is out of pipeline, they do not prevent rapid deceleration of water column when all air is out of the pipeline. Besides, an improperly sized non-slam air valve may not switch to a smaller outflow orifice before all air is out of pipeline and can lead to full air slam pressure. Since the instantaneous deceleration of water column after all air is out of pipeline is the main cause of air slam pressures, dynamically extending the deceleration of water column over a short duration can virtually eliminate air slam pressures. Allowing the water column to continue to move through the air valve by keeping it open after all air is out of pipeline and then closing the valve over a short duration will accomplish this task. Such types of air valves are referred to as dynamic air valves.




**Surge Modeling.** A mathematical model was created in Surge2012 software for the Kalanit Pipeline System incorporating main and secondary pipelines, pump station details including pump discharge line and check valve characteristics, existing air valves, and the temporary connection to the elevated storage reservoir acting as one-way surge tank (cushioning reservoir). Preliminary studies with existing kinetic air valves have indicated the potential for air slam conditions and subsequent overpressures throughout the pipeline system. Significant over pressures were noted with or without cushioning reservoir. Preliminary studies also indicated substantial reduction in over pressures when existing kinetic air valves were replaced by non-slam and dynamic air valves of equivalent sizes. A controlled field testing study was undertaken to validate model results before finalizing the replacement of existing air valves with non-slam and/or dynamic air valves.

In order to have a better control over the field experiments, flows from PS-2 and PS-3 were isolated from rest of the system and only single pump operation at PS-1 was considered. Cushioning reservoir was charged and connection to cushioning reservoir was activated. In addition, all air valves along the primary flow path were replaced with 100mm dynamic air valves to minimize the potential for air slam at non-critical air valves. These valves were set to open in 0.5s from fully closed to fully open mode and set to close in 1.3s from fully open to fully closed mode. Figure 3 shows the profile view of KPS along the main flow path from PS-1 to delivery end.

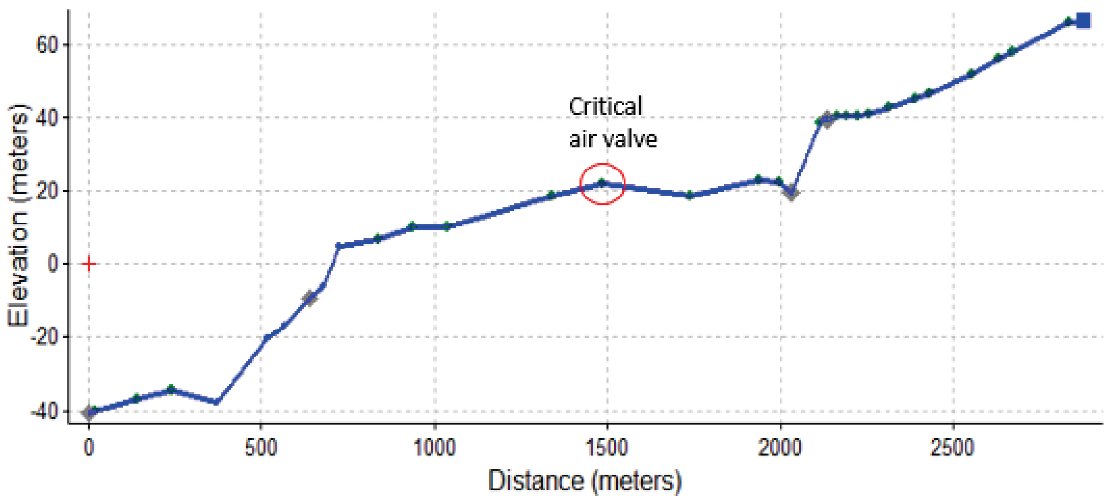



*Figure 3. Pipeline profile from PS-1 to delivery end along main flow path*

Each pump at PS-1 was rated for $390m^3/h$ of flowrate at 314m of head. Rated speed for the pump was 1450 RPM. In the absence of reliable dynamic characteristics, the swing check valves at pump discharge were modeled as simple check valves with linear closing pattern and were set to close in 0.5s from the time of flow reversal. Demands at nodes catering for the settlements near PS-1 were modeled as pressure sensitive demands. Since the air valve at the critical location was mounted on a fairly long (2.5m) riser, the riser was modeled as a pipe element to capture the proper wave action between the air valve and main delivery line. A pump trip scenario was specified after 10s from the start of simulation.

Field experiments were carried out with three different types of air valves at the critical location: existing kinetic air valve, a non-slam air valve and a dynamic air valve. Three high speed data loggers capable of measuring pressure readings at a rate of 1000Hz were used. One data logger was connected to a transducer located at the critical air valve. The other two were connected on upstream and downstream sides of check valve of the operating pump at PS-1.

**Results.** Figures 4, 6, and 8 show the measured pressure traces at critical air valve location with three different air valves at that location – kinetic, non-slam and dynamic air valves. Figures 5, 7, and 9 show the corresponding pressure traces obtained from transient models. The model predicted highest surge pressure values match closely to the corresponding measured values for all three cases. For the case of kinetic air valve at critical location, the highest surge pressure measured was nearly 17.5bars and the model predicted value was slightly below 18bars. Figure 10 shows model predicted air volume curve and the associated pressure within the kinetic air valve. Figure 11 shows variation in flowrate in the riser pipe connecting kinetic air valve to the main pipeline. Air flows into the pipeline from about 13.2s for about 0.5s and out of the pipeline from 13.7s to 14.2s. Water column behind the air column decelerates rapidly on complete expulsion of air resulting in significant air slam pressure. Flow velocity within the riser pipeline reaches nearly 5.5m/s (flowrate of 350 $m^3/h$ in 150mm pipe) just before the complete expulsion of air.


Figures 12 and 13 show air volume, pressure and flowrate variations for the case of non-slam air valve at critical location. The maximum flow velocity in the riser pipe reaches about 4.2 m/s just before complete expulsion of air as air flows through smaller orifice towards the end of air outflow cycle. Smaller flow velocity just before the complete expulsion of air results in smaller air slam pressure compared to the case of kinetic air valve at critical location.

Figures 14 and 15 shows air volume, pressure and flowrate variations for the case of dynamic slam air valve at critical location. The maximum flow velocity in the riser pipe reaches about 5.5 m/s just before complete expulsion of air and is same as that corresponding to flowrate through kinetic air valve. However, unlike kinetic and non-slam air valves, flow does not drop rapidly to zero on complete expulsion of air! Instead, water continues to flow out of air valve and the valve closes slowly in about 1.3s bringing flow velocity to 0 in a highly controlled manner and thereby eliminating the slam conditions. Figures 16 and 17 compare measured and model predicted pressure variations at check valve location for the case of dynamic air valve at critical location.

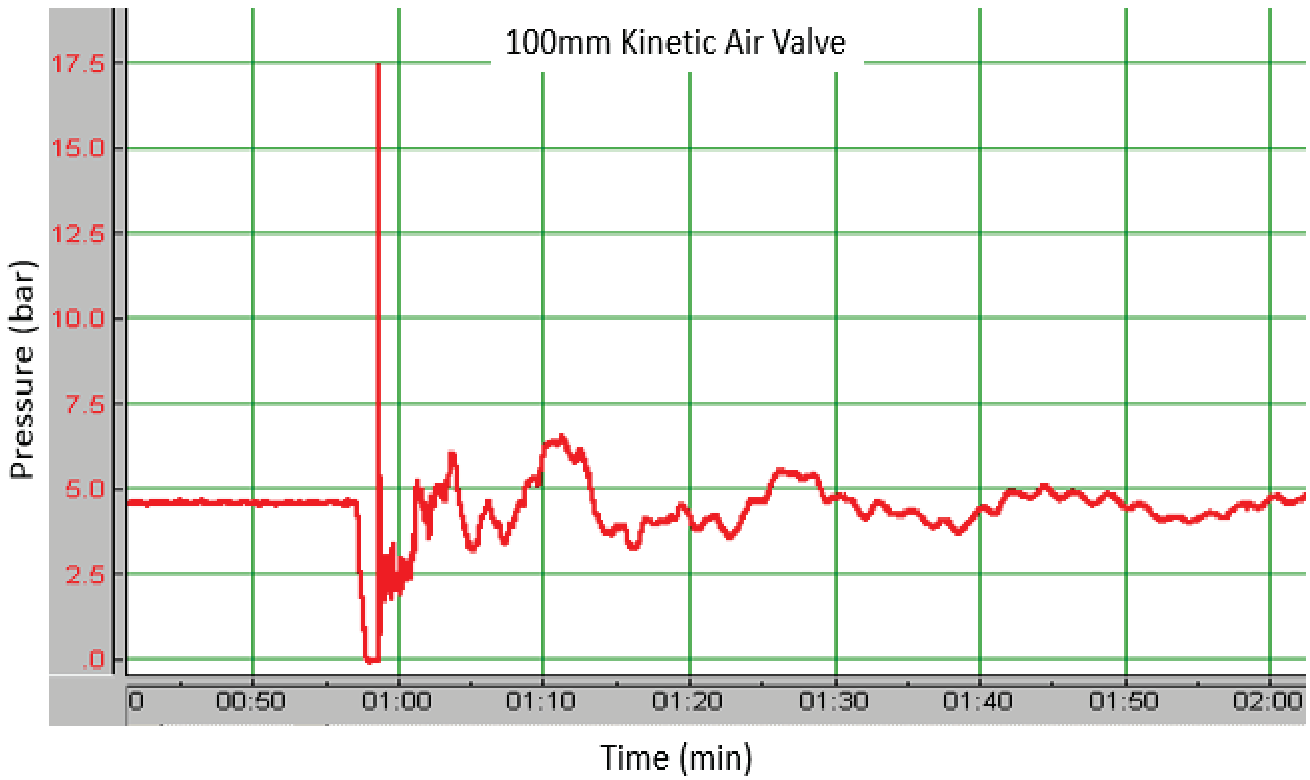



Figure 4. Variation in <u>measured</u> pressure at critical air valve location with kinetic air valve

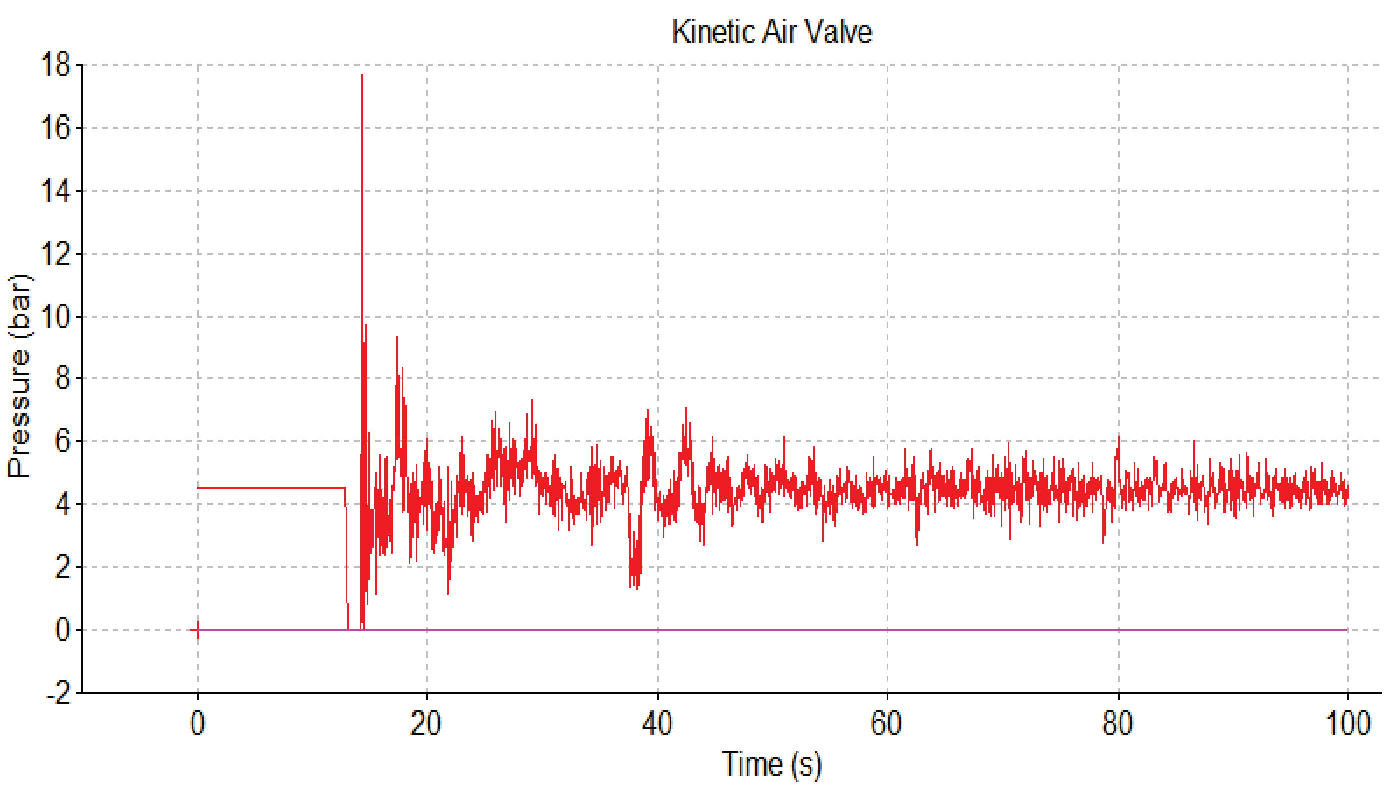



Figure 5. Variation in <u>model</u> pressure at critical air valve location with kinetic air valve

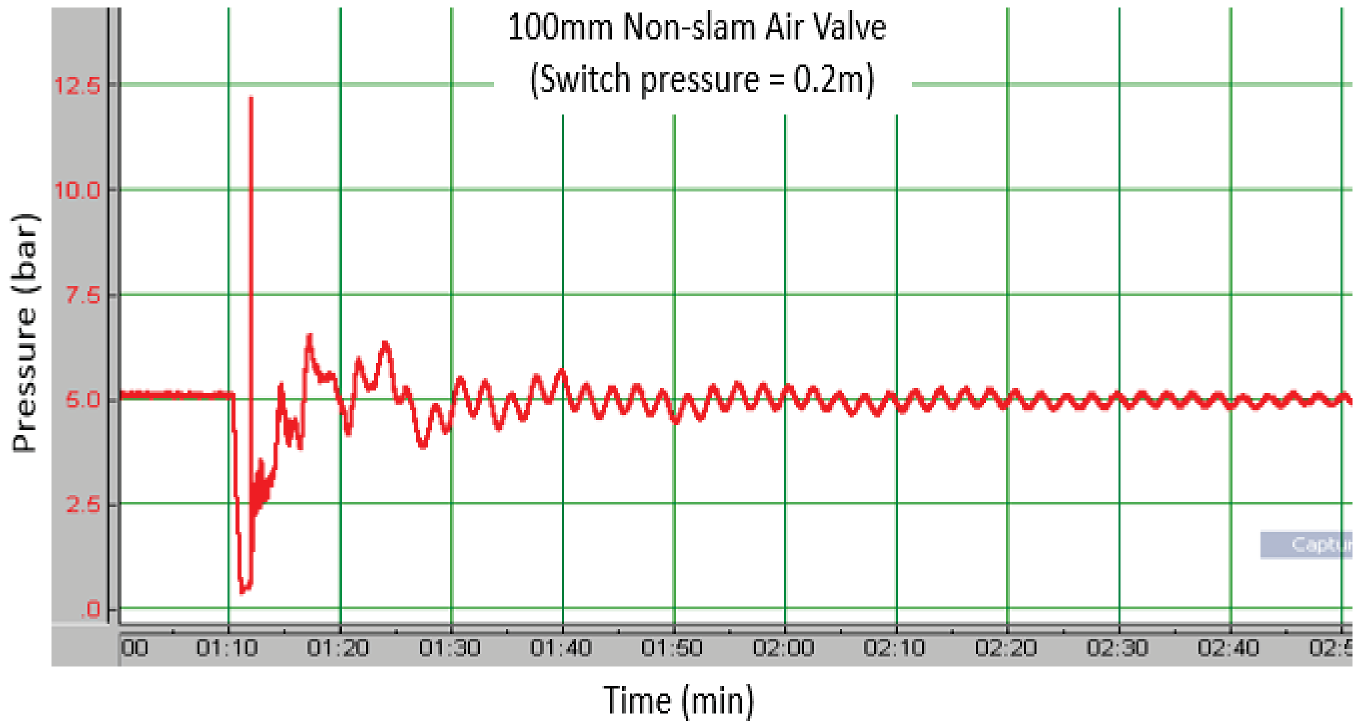



Figure 6. Variation in <u>measured</u> pressure at critical air valve location with non-slam air valve

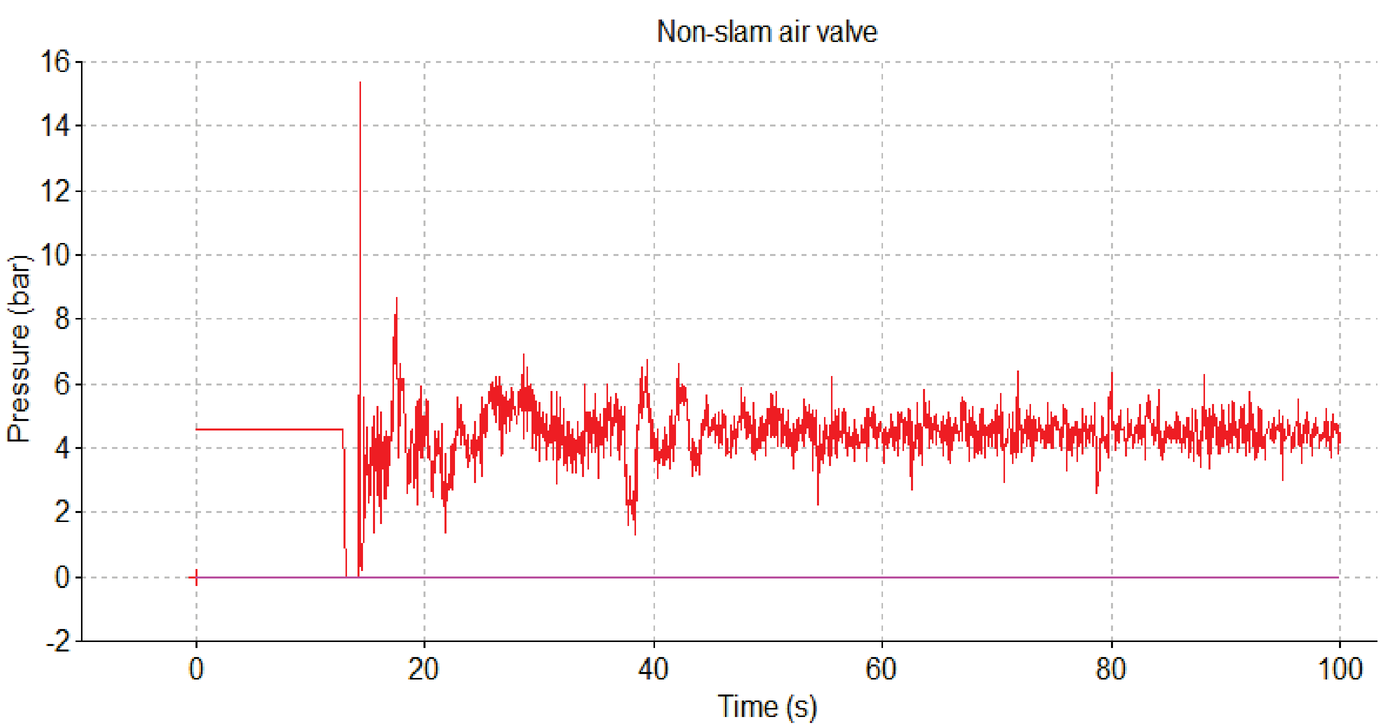



Figure 7. Variation in <u>model</u> pressure at critical air valve location with non-slam air valve

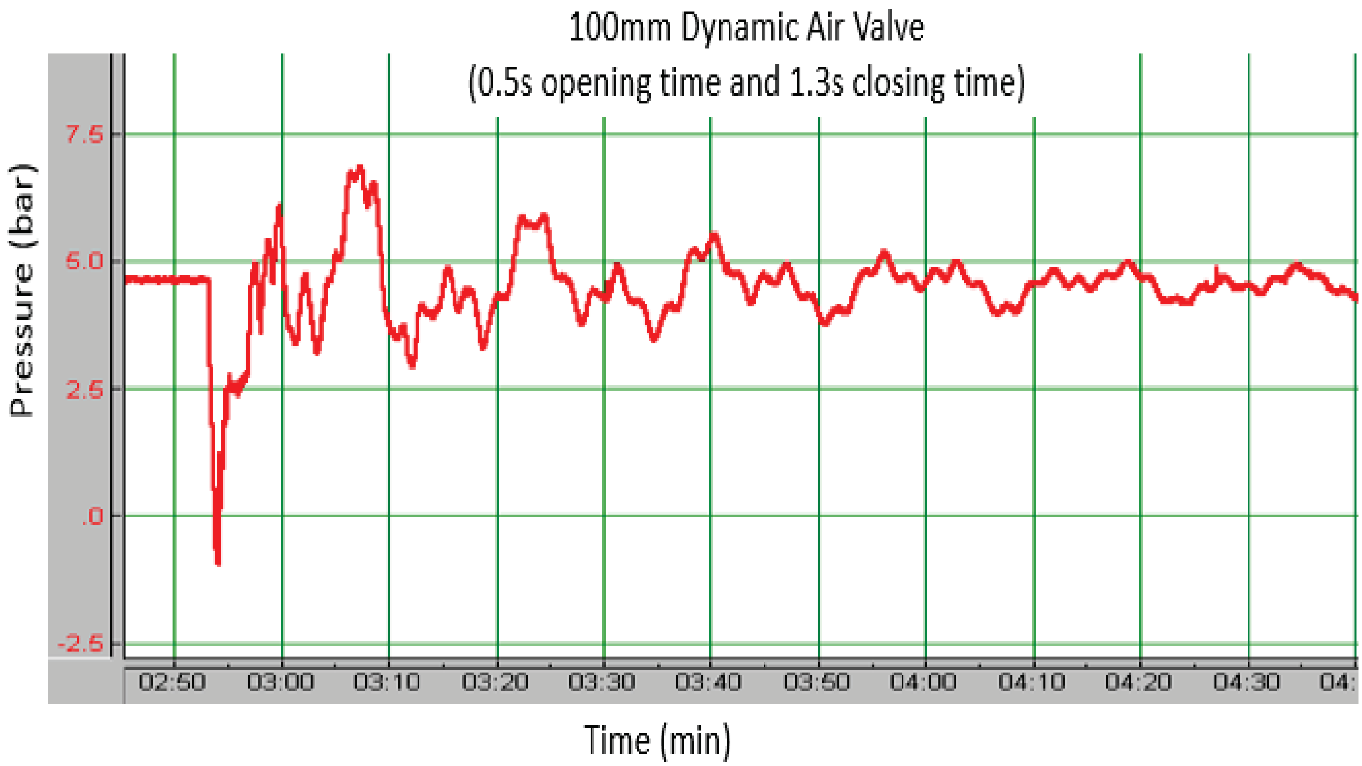



Figure 8. Variation in <u>measured</u> pressure at critical air valve location with dynamic air valve

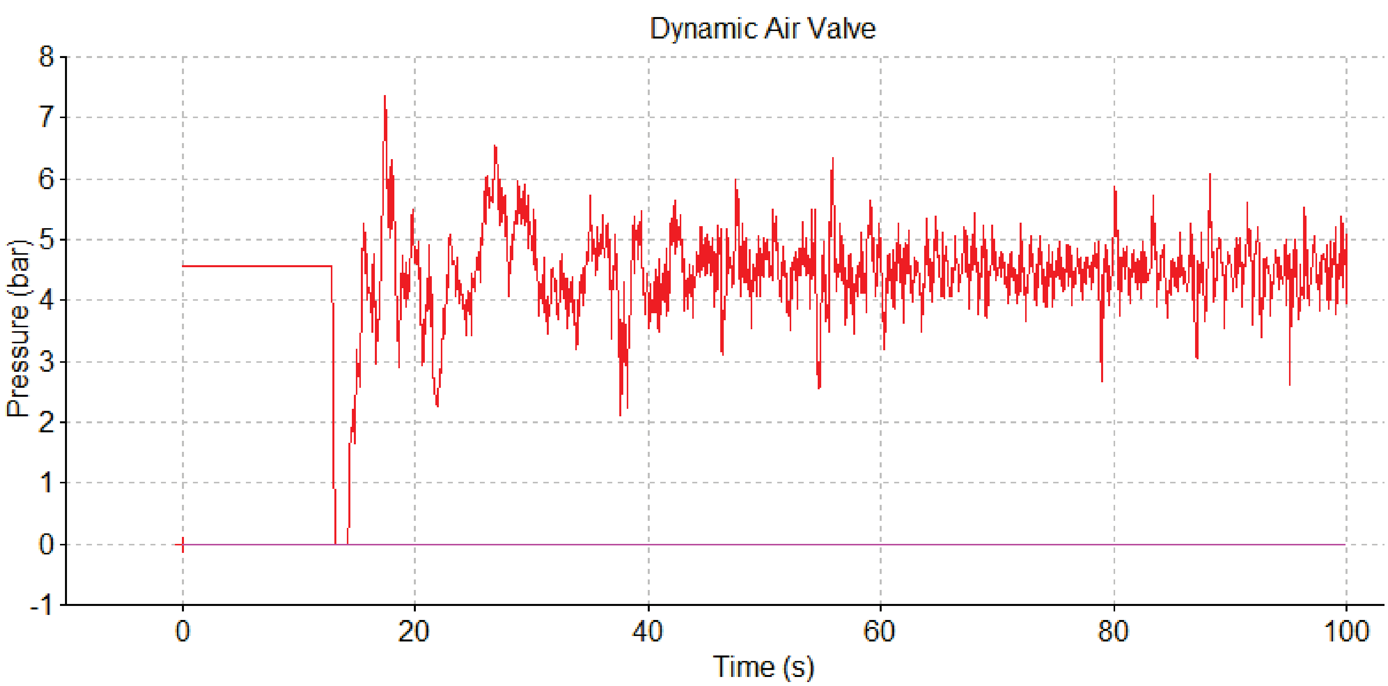



Figure 9. Variation in <u>model</u> pressure at critical air valve location with dynamic air valve

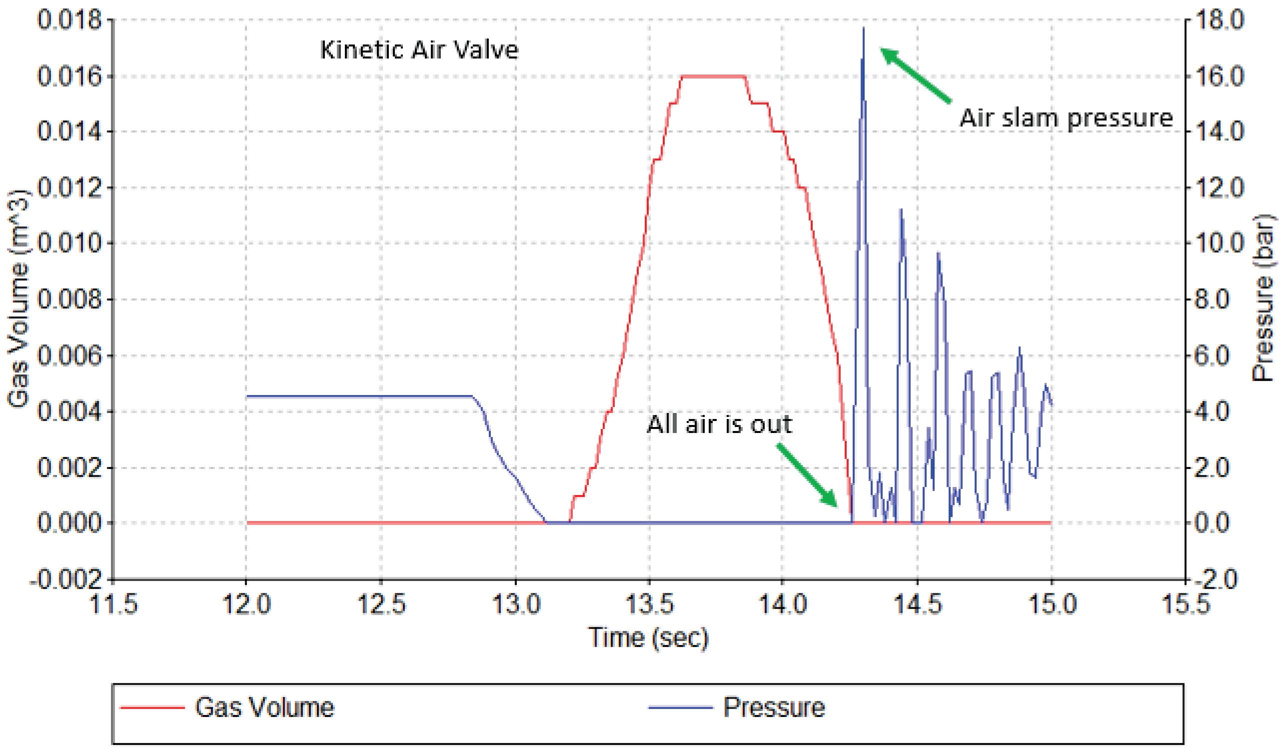



Figure 10. Variation in air volume and the associated pressure within kinetic air valve

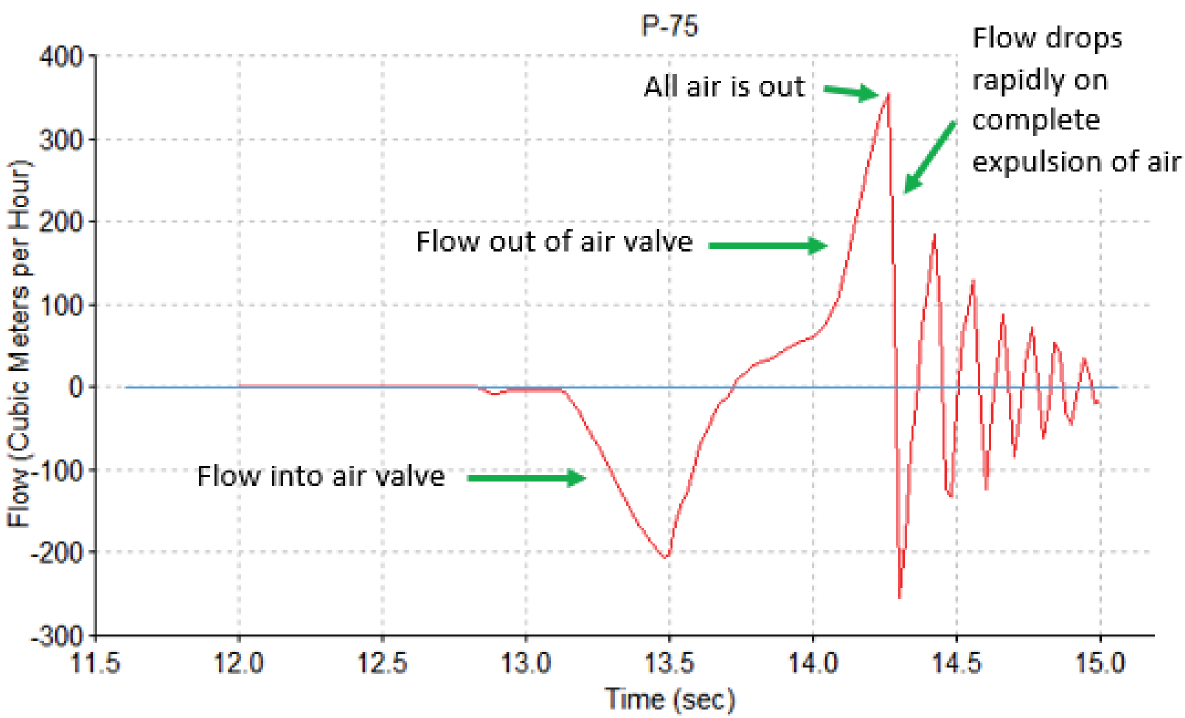



Figure 11. Variation in flowrate in riser pipe connecting kinetic air valve at critical location

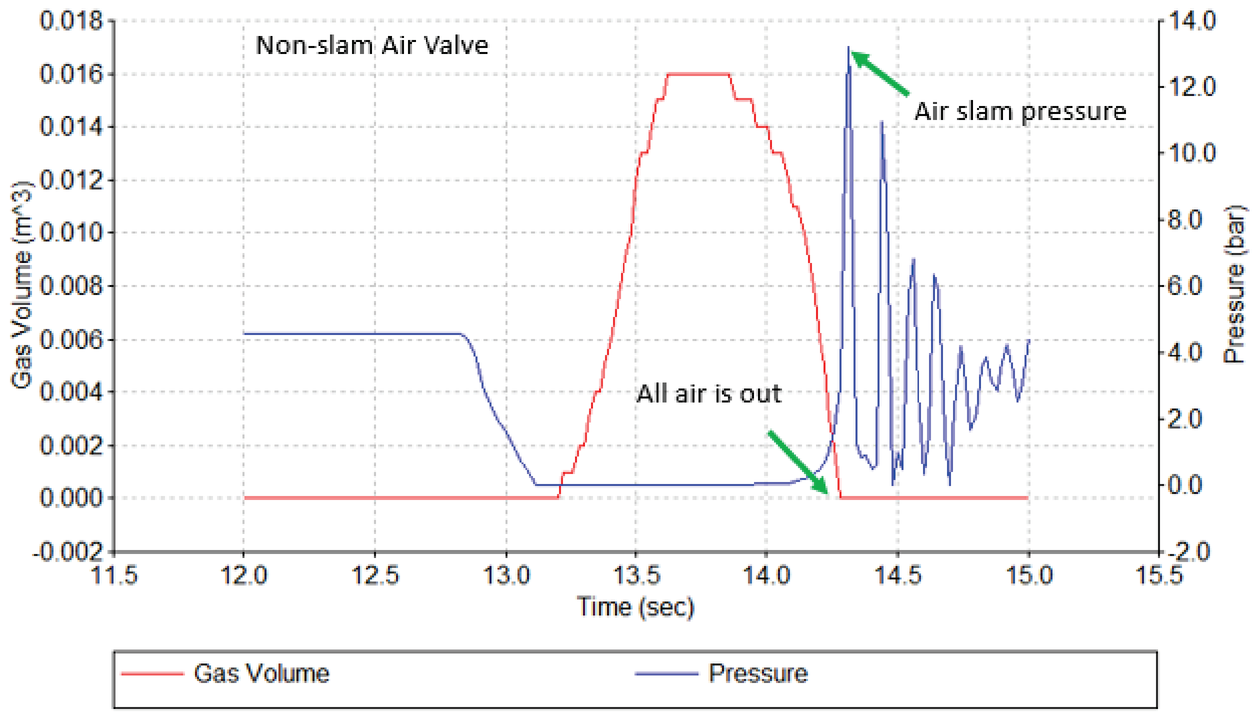



Figure 12. Variation in air volume and the associated pressure within non-slam air valve

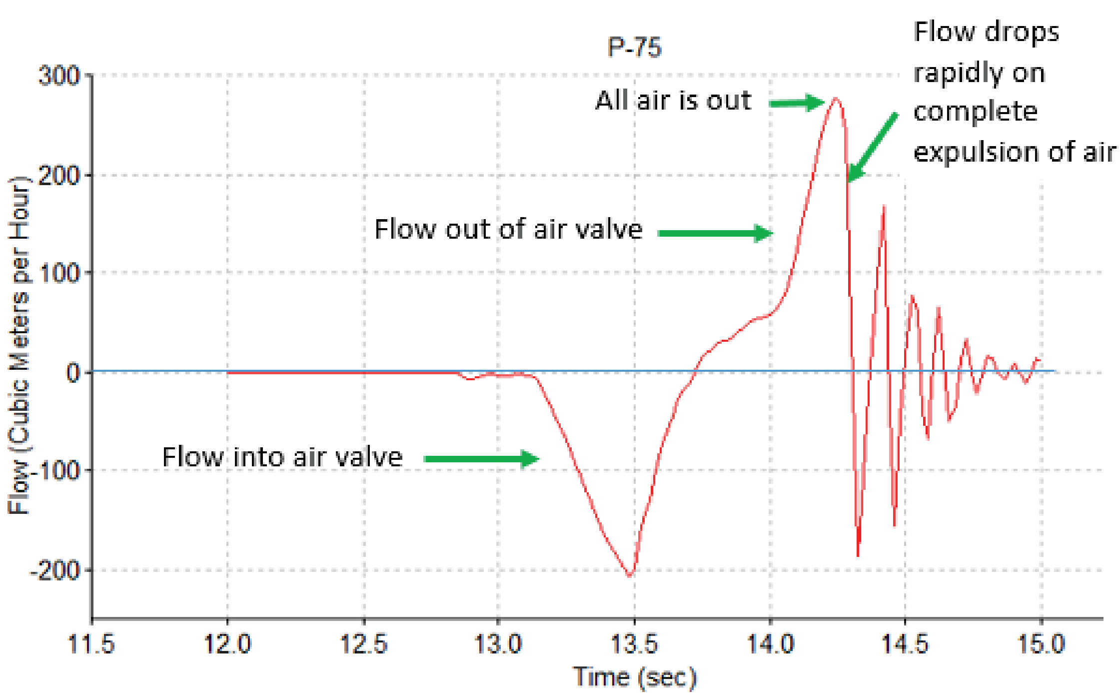



Figure 13. Variation in flowrate in riser pipe connecting non-slam air valve at critical location

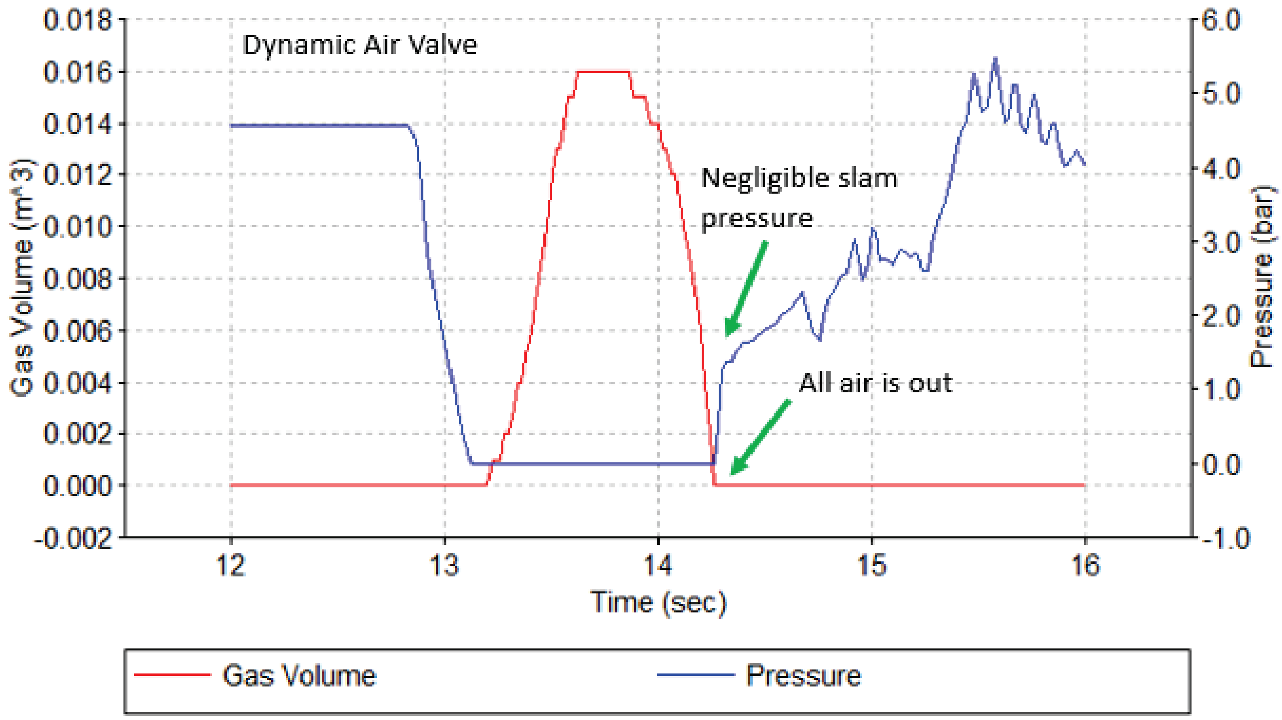



Figure 14. Variation in air volume and the associated pressure within dynamic air valve

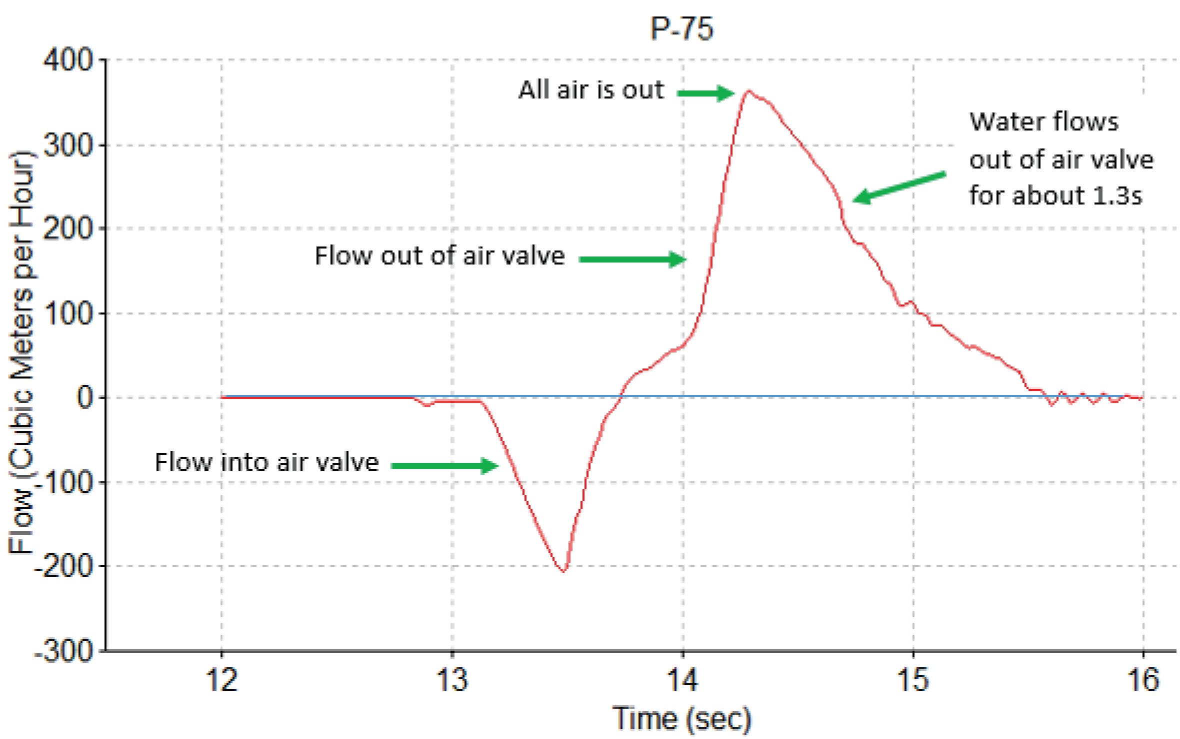



Figure 15. Variation in flowrate in riser pipe connecting dynamic air valve at critical location

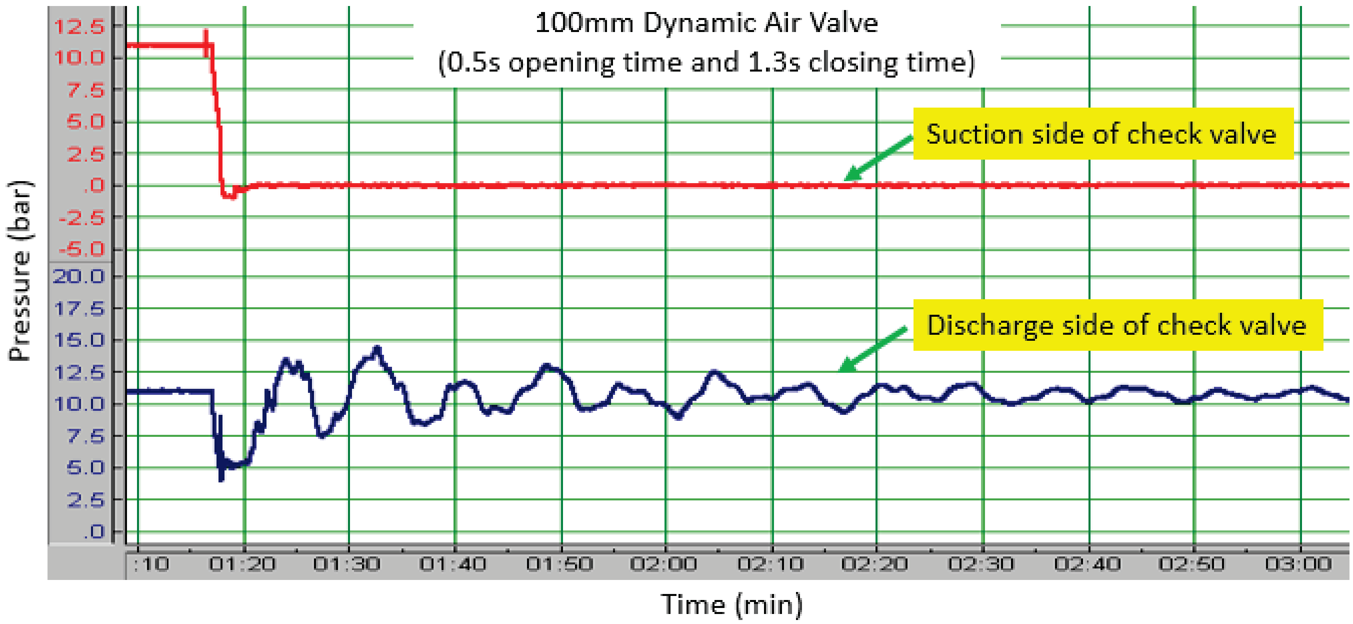



Figure 16. Pressure variation (measured) at check valve with dynamic air valve at critical location

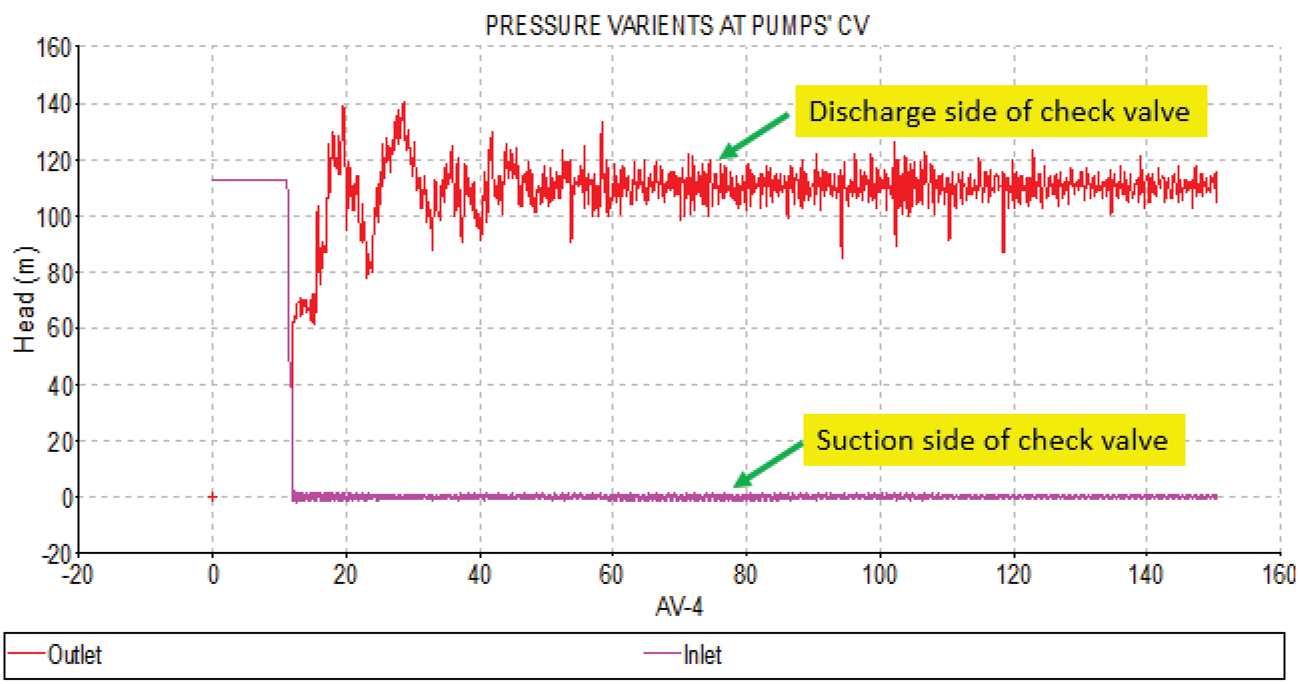



Figure 17. Pressure variation (model) at check valve with dynamic air valve at critical location

**Conclusions.** Air slam can be a serious issue when there are ordinary air/vacuum valves on pipeline systems whether for normal filling/draining operations or for surge protection. Conventional non-slam air valves may not be effective all times and may not mitigate air slam conditions unless pressure and flow conditions are appropriate for the switch to activate from larger outflow orifice to smaller outflow orifice. Low volumes of air (into the pipeline) and large switch pressures may reduce the reliability and effectiveness of conventional non-slam air valves in providing the expected non-slam effect. Field measurements showed significant over pressures resulting from air slam conditions at a kinetic air valve in a fairly large pipeline system that has experienced repeated damages following pump trip events. Transient models were able to accurately predict the air slam pressures and allowed for determining remedial measures by way of conventional non-slam air valves and the new breed of dynamic air valves. Measured and model predicted values compared well for all three cases of air valves (kinetic, non-slam, and dynamic) at the critical location along the pipeline system. Use of dynamic air valve prevents rapid deceleration of water column behind the air volumn which in turn minimizes the air slam conditions and the associated over pressures.

## References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