PRESSURE SURGE MITIGATION AT HIGH TEMPERATURE TUBE DIGESTION FACILITY OF YARWUN ALUMINA REFINERY

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Abstract

The Yarwun Alumina Refinery identified the potential for high transient pressures through its tube digestion unit during operational upsets. As a result, these transient conditions can potentially expose plant, equipment and personnel to operational safety risks. Through extensive dynamic hydraulic modeling efforts, Hatch Associates assisted the refinery to investigate the potential causes of high transient pressures. Recommendations to either prevent or mitigate potential pressure surges were then made. This paper describes the methodology and tools used in establishing a dynamic hydraulic model for the piping system The model was then used to explore a number of mechanically passive protection measures, such as allocating and/or increasing surge dampers and modifying the isolation angle valve mechanical design, to mitigate the pressure surge. In addition to administrative controls, other instrumentation measures were also investigated to contribute to the layers of overpressure protection. The recommended measures are currently being implemented at the refinery.

1. Introduction

The refinery currently has two operating digestion units using a proprietary high temperature tube digestion technology with a total plant output of 1.4 Mtpa alumina. Figure 1 illustrates a simplified equipment diagram of each digestion unit. Each unit has 3 trains of 10-stage recuperative Jacketed Pipe Heaters (JPH) of gradually increasing temperature and 1 shared common flash train of 10-stage flash tanks. Final digestion holding temperature of 280°C is achieved through additional stages of JPH heated by high pressure live steam. Cold bauxite slurry of each train is pumped by a dedicated piston-diaphragm positive displacement pump, referred to as PD pump herein after. The JPH's of each train are periodically taken out of service for hydro blast cleaning of the tubes to maintain heat transfer performance. At the end of each train, a back pressure control valve (BPCV) of an annular plug type operates constantly to maintain an upstream pressure of the holding tubes above the boiling point pressure in accordance with the slurry operating temperature. Located downstream of this control valve, there is a manual isolation valve which isolates the train flow from the other heater trains. This manual isolator is located on the Back Pressure Pipe– a mixing chamber where all three heater trains combine.

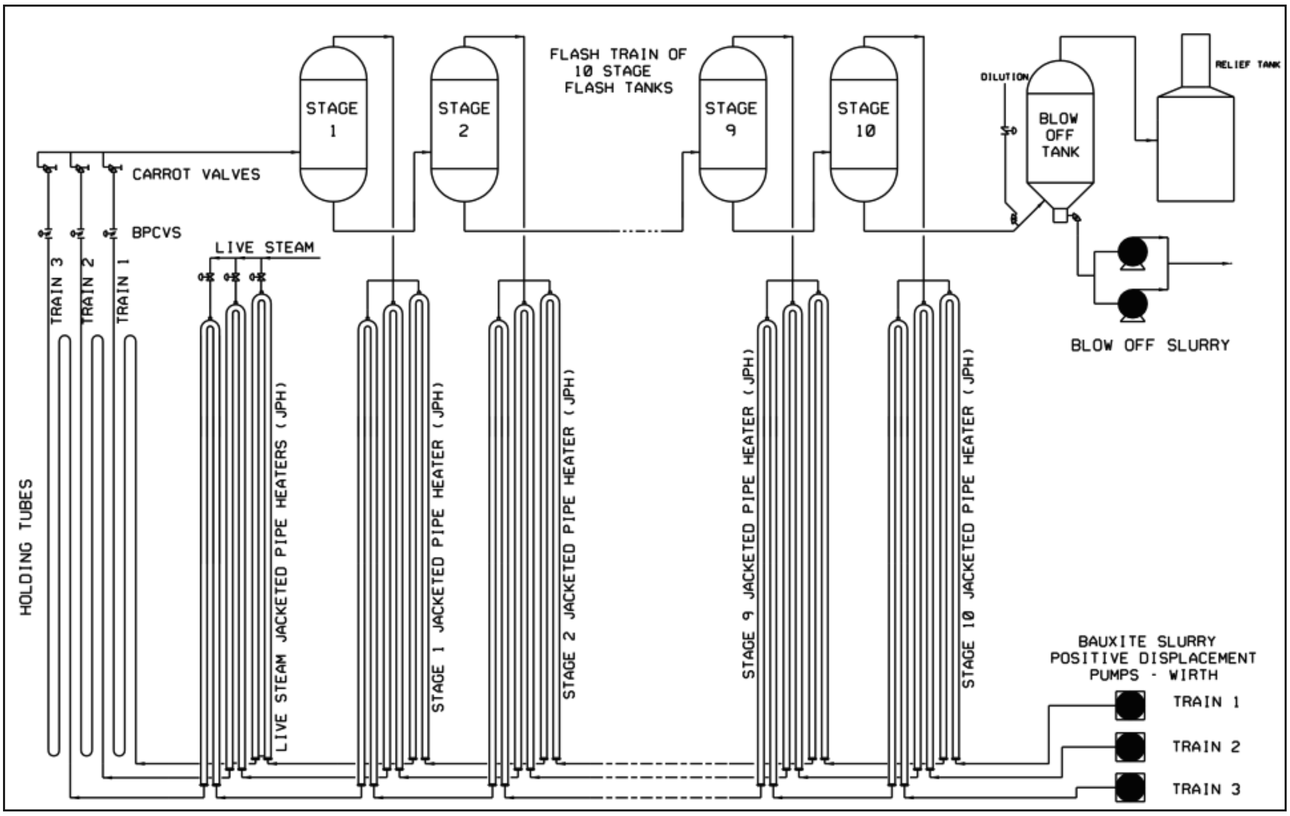

Figure 1. Digestion Unit Schematic

The high pressure surges investigated in this paper were based on assuming inadvertent closure of the Back Pressure Pipe isolation valves or BPCV while the train is still live, i.e. its PD pump was still pumping the hot slurry through the train. The resultant pressure surge is a phenomenon known as "standing pressure waves" (water hammer) generated, propagated and locked in the piping system when closure of the valve is almost instantaneous.

There are many techniques for controlling pressure transients with varying potential solutions depending upon the initiating event and how the resulting up/down surge develops. Without a fundamental understanding of hydraulic dynamics, arbitrary application of a solution may in fact exacerbate the associated fluid column separation (and where applicable, vapour-pocket collapse) which can significantly amplify the pressure surge and impose even greater risks to the piping system integrity.

In order to understand and quantify the factors contributing to the pressure surges and identify the most effective mechanisms to mitigate the surge peak to a safe level, a dynamic hydraulic transient model was developed. This model enabled numerical simulation of the mathematics behind this complex physical phenomenon, and was developed using specialised computer programs based on algorithm referred to as "Method of Characteristic" technique to solve constitutional differential equations of mass, energy and momentum equilibriums [1][2]. The various models used were based on a simplified physical piping and equipment network for one of the three trains starting from the bauxite slurry mixing tank to the Stage1 flash tank of the Unit 1 flash train.

Two independent transient simulation models were developed for comparative purposes to provide integrity in the simulation results. Predictions of potential pressure surge were then made using the models for various flow conditions including maximum flow. Various opportunities to mitigate the surge pressures were investigated.

2. Modelling

2.1 Description of physical piping network

Digestion train flow starts from an elevated surge tank. The PD pump is a triplex single acting diaphragm pump incorporating spring assisted non-return valves at both the suction and discharge manifold. The pump delivers a pulsating flow of average 351~410m^3/hr with a variable stroke rate of 54~60rpm. Figure 2 plots instantaneous flow of the pump at 59 rpm stroke rate over 0~360^o crank shaft phase angle. Upstream of the suction check valve there is an air vessel type pulsation damper to maximize NPIP (Net Positive Inlet Pressure) available to the pump by minimizing the suction acceleration head loss. Suction piping to the pump is not the focus of modelling in this paper.

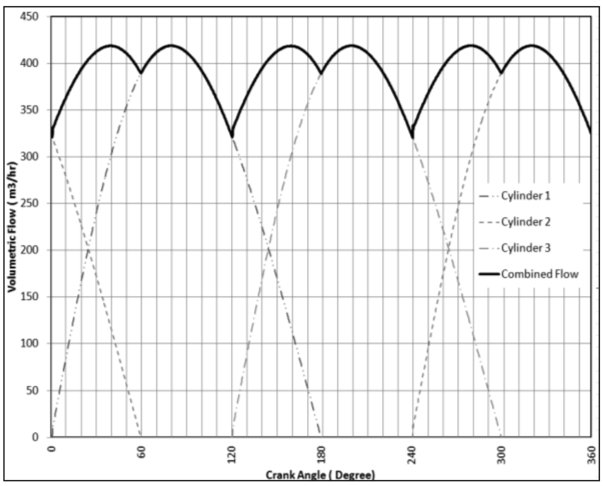

Figure 2 - Triplex PD Pump Discharge Flow Pulsation

Downstream of the discharge check valve there is a discharge dampener designed to attenuate the normal nature of flow pulsations (per Figure 2) associated with the positive displacement pump. Table 1 lists slurry operating level 'H' and calibration level with the corresponding air volumes of the existing dampener which were used in the model calibration. The pump, valves and dampeners are all installed at ground level. The discharge slurry line from the discharge dampener is distributed into the commencement of the 12 stage JPH run. Downstream of the JPH's, the slurry flow is eventually distributed into the Back Pressure Station. Following this, the 3 heater trains are ultimately combined in the Back Pressure Pipe prior to discharge to the Stage 1 flash vessel.

The Back Pressure Pipe isolation valve is an angle type valve with plug disc (~305mm seat bore). Table 2 below shows the theoretically interpreted valve characteristic data at different percentages of opening for the valve used in the transient model. The BPCV is a proprietary parabolic profiled annular plug type angle valve of F250mm seat bore size.

From a modelling perspective, a few assumptions/simplifications were applied where equipment or plant data could not be adequately quantified:

a) the Back Pressure Pipe isolation valve closure speed was estimated;
b) the PD pump Interlock trip timing and inertia when stopping was estimated;
c) the response time period from the initiation of the pressure surge to the pump tripping was estimated,

Table 1–Discharge Dampener Level & Air Volume

Level H(mm)	Calibration Level (%)	Initial Air Vol. (Liter)	Initial Liquid Vol. (Liter)
0	0	1599	370
600	25.4	1248	721
673	28.5	1205	764
1100	46.6	1014	955
1529	64.7	703	1266
2363	100	214	1755

Table 2 – "Carrot" Valve Flow Characteristics

Valve Opening (position based)	K Factor	Cv (usgpm/psi $^{0.5}$)	Valve Opening (Cv based)
100 %	2	3049	100 %
90 %	2.2	2907	95 %
80 %	2.4	2783	91 %
70 %	2.5	2727	89 %
60 %	2.9	2532	83 %
50 %	3.2	2410	79 %
40 %	4	2156	71 %
30 %	5.5	1838	60 %
20 %	10	1363	45 %
10 %	38	699	23 %
0		0	0

2.2 Basis of Pressure Transient Modelling

Throughout the study, the fluid, which is bauxite slurry of ~10% solid concentration, was assumed to exhibit Newtonian fluid flow behaviour and no cavitating or flashing phase changes. Cold end slurry density and viscosity data was used throughout JPH ignoring temperature effects. The boundary to large vessels/

tanks for modelling was chosen such that deviation from reality is minimized. The range in discharge dampener level was taken as a minimum level of 30% and maximum level of 70%. The 2-stage geared Back Pressure Pipe valve closing duration of 30 minutes (25+5 min) was scaled down to a total two staged closing duration of 192s (180 +12 seconds) for modelling. The second stroke of 12 seconds for final closing was based on two intervals of ~ 6 seconds, which classifies the valve closure as a "gradual" class.

When modelling the Back Pressure Pipe valve transients, the BPCV was assumed to stay its initial opening condition during the transient because of its slow action actuator. The wave celerity (speed) was calculated to be in the range 1,067 to 1,160 m/s. Pump inertia after a pump trip was considered in the modelling through an estimated gradual reduction in pump speed.

Figure 3 illustrates the Back Pressure Pipe valve closing characteristics expressed in the form of percentage of valve flow passage relative area v.s. percentage of valve relative closure position. The inherent valve's closing characteristic is slam shut at full closure as indicated in the figure.

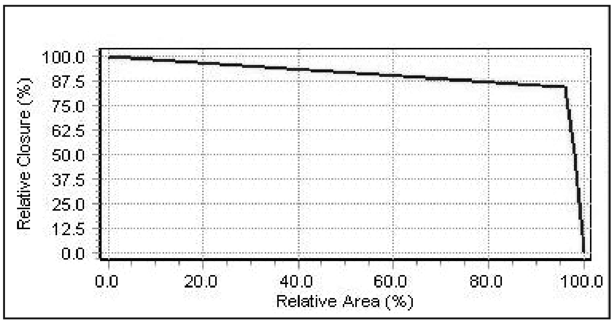

Figure 3 Input of Back Pressure Pipe Valve Closing Characteristics

2.3 Pressure Transient Modelling

Figure 4 illustrates a diagram of the hydraulic model developed for the digestion piping network described in Section 2.1. Table 3 bellow lists details of each hydraulic component in the diagram.

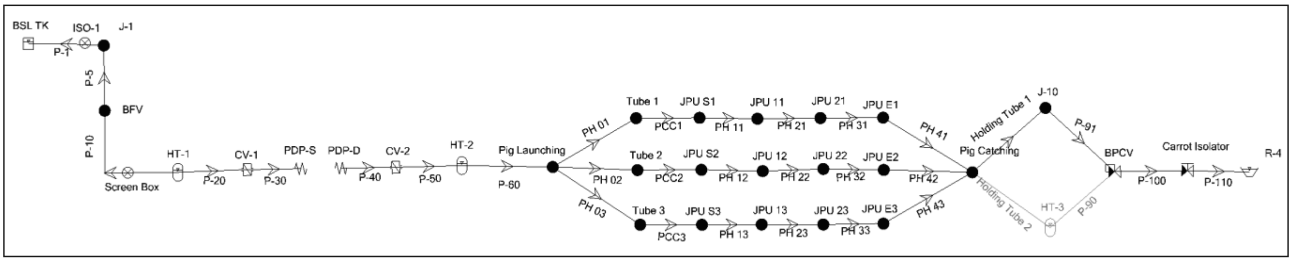

Figure 4 Typical Diagram of the Hydraulic Model

Figure 5 below plots both flow and pressure transient for a 350-second simulation. In this simulation, the accumulator had 65% liquid level, the Back Pressure Pipe isolation valve reached 93.4% closure at a time of 180s and full shut at time of 192s. The positive displacement pump was tripped at t=186s, 6 seconds after the full valve closure and was brought to a complete stop in 12 seconds duration. After full closure of the valve, the valve remained closed for a 98 second interval before being opened again over a 38 second period. The valve remained open for 12 seconds until the 350-second simulation period ended. Some sensitivity analysis was conducted and reported by a number of cases in Table 4 in order to evaluate the significance of these parameters.

Following analysis and quantification of the pressure surge (Fig 5) a number of simulations using the model in Fig.4 were performed to investigate opportunities to reduce the peak of the surge pressure in the event of an inadvertent Back Pressure Pipe valve isolation[3]. One of the intrinsically safe pressure surge mitigation methods was to look at:

1) increased size of the discharge accumulator
2) allocation of an additional new accumulator upstream of the Back Pressure Pipe manual isolator and BPCV valve.

Table 4 summarizes the cases explored under various operating conditions indicated as well as pump trip scenarios. Unless otherwise noted, a pump trip in 6 sec and subsequent complete shut in 12 sec was used for most of the cases reported. Under the provisions of ASME B31.3, temporary overpressures of 33% above MAWP is permitted for piping systems subject to certain coincident compliant conditions. The aim of mitigating the surge peak to be below 133% of an MAWP of 8,872 kPag at the hot slurry end of 280°C (and 10,270 kPag at the cold slurry end of 90°C), was found to be impractical because this would require either a huge size ~7.2m^3 (Case 9) for a single accumulator or ~2.5 m^3 each for two accumulators (Case 12) to be implemented. For the double accumulator approach, it was viewed to be problematic for future wet oxidation at the time of the study.

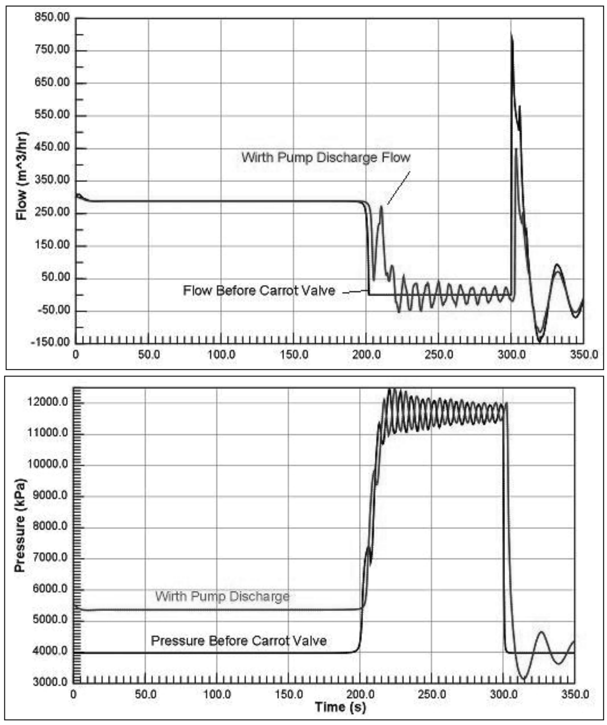

Figure 5 Transient Model Calibrations – Flow & Pressure Plots

The Back Pressure Pipe's valve's closing characteristic also affects the surge pressure peaks and is considered to be another opportunity for the pressure transient mitigation. Figure 6 illustrates representative valve characteristics from typical valves, with the manual isolator representing the fast opening characteristic. Table 5 summarises a comparative review of the potential pressure surge peak reduction by modifying the manual isolator's valve plug characteristics from the current fast acting curve present in the standard angle valve disc to that representing a more linear valve characteristic typical of an equal percentage globe valve or slower acting butterfly. The effect of instantaneous closing speed at the valve's full closure was also examined. The results suggested an optimal valve plug configuration approaching the equal percentage would offer up to a 13-18% reduction in magnitude of the pressure surge peaks.

Table 3 – Main Components Listed in Fig.4 Diagram

Element		Representing Equipment
Name	Type	
BSL TK	Tank	Slurry mixing feed tank
HT-1	Hydro pneumatic tank	Pump suction accumulator
CV-1	Check valve	Pump suction check valve
PDP-S	Periodic Flow Element	Pump suction end
PDP-D	Periodic Flow Element	Pump discharge end
HT-2	Hydro pneumatic tank	Pump discharge accumulator
CV-2	Check valve	Pump discharge check valve
BPCV	Pressure Sustaining Valve	Back pressure control valve
Carrot	Throttle Valve	Carrot isolation manual valve
R-4	Reservoir	1st Flash tank

Table 4 Conditions and Results of Cases Studied

Case No.	Discharge Accumulator (Litres)			Surge peak Pressure (kPa,g)	Notes
	Air	Liquid	Total		
Conditions: Flow 289m3/hr; Backpressure 4372kPag;					
Case 1	1599	370	1969	10134	1,5
Case 2	1599	370	1969	11493	1,6
Case 3	1800	721	2521	9812	2,5
Case 4	2600	721	3321	9980	2,6
Conditions: Flow 351m3/hr; Backpressure 5651kPag;					
Case 5	1800	721	2521	13635	2,5
Conditions: Flow 351m3/hr; Backpressure 6000kPag;					
Case 6	1800	721	2521	15245	2,5
Conditions: Flow 386m3/hr; Backpressure 6000kPag;					
Case 7	1800	721	2521	16927	2,5
Case 8	1205	764	1969	18116	3,5
Case 9	6500	721	7221	10915	2,5
Conditions: Flow 410m3/hr; Backpressure 6000kPag;					
Case10	4000	721	4721	12745	2,5
Case11	5000	721	4721	12120	2,5
Two identical air accumulators, the 2nd before BPCV. Conditions: Flow 410m3/hr; Backpressure 6000kPag;					
Case12	1800	721	2521	11118	4,5
Sensitivity study of different timing of pump shut and duration; Conditions: Flow 351m3/hr; Backpressure 6000kPag;					
Case 13	2600	721	3321	15567	2,5
Case 14	2600	721	3321	13858	2,7
Case 15	2600	721	3321	10263	2,8

Notes:

1. Existing accumulator size at 0% liquid level per Table 1;
2. Increased accumulator size however maintained existing ID of 864mm. Liquid volume of 721 litres corresponds to lower limit of the target liquid level;
3. Existing accumulator size at 28.5% liquid level per Table 1;
4. Two air accumulators deployed;
5. Pump trip in 6 sec and shut in 12 sec;
6. Pump trip in 6 sec and shut in 18 sec;
7. Pump trip in 2 sec and shut in 12 sec;
8. Pump trip in 2 sec and shut in 6 sec;

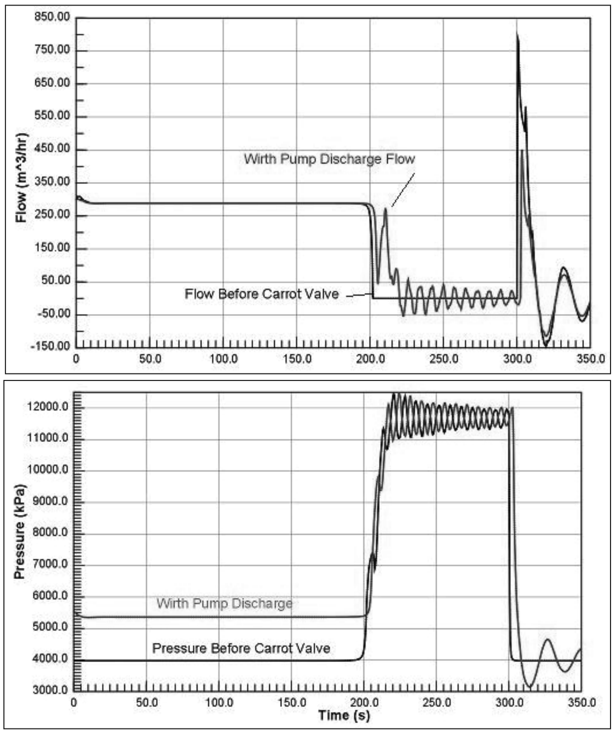

Figure 6 Typical Valve Plug Profile and Inherent Cv Characteristics

Table 5 Pressure Surge Peak Reduction with Slower Closing Characteristics of Manual Isolator

Fow (m3/hr)	Back Pressure (kPag)	Valve closing from ~90% to 100% (second)	BASE CASE (Existing Valve)		Linear Valve	Characteristic	Butterfly Valve(Best Characteristic)	
			peak presssure kPag	Surge peak presssure reduction (%)	peak presssure kPag	Surge peak presssure reduction (%)	peak presssure kPag	Surge peak presssure reduction (%)
289	4370	60	6,888.80	100% (Base)	6,118.70	11.2	5,945.10	13.7
		12	7,331.60	100% (Base)	6,832.60	6.8	6,057.30	17.4
		5	7,393.60	100% (Base)	7,164.00	3.1	6,328.00	14.4
386	6000	60	9,630.40	100% (Base)	8,660.20	10.1	8,416.50	12.6
		12	10,110.20	100% (Base)	9,571.30	5.3	8,574.60	15.2
		5	10,172.70	100% (Base)	9,934.50	2.3	8,935.90	12.2
410	5600	60	9,432.30	100% (Base)	8,302.30	12.0	8,020.10	15.0
		12	10,020.30	100% (Base)	9,356.30	6.6	8,205.50	18.1
		5	10,073.80	100% (Base)	9,807.30	2.6	8,618.60	14.4

2.4 Modified 2-Stage Carrot Valve Plug Concept

As Case 14 and 15 in Table 4 suggest, a trip of the pump at a much earlier time than 6 seconds and its complete stop at much faster rate than 12-second duration will significantly reduce the pressure surge peak. Whilst the second remedy requires braking of the pump and /or pump motor, which was not investigated in this paper, the first approach essentially requires some design attempt to sever or minimize the link between full valve closures and pump dead heading. Figure 7 illustrates a conceptual design of a modified 2 staged Back Pressure Pipe valve plug approaching equal percentage globe with extended body trim. The graph on the right shows an ideally slow closing Cv characteristic curve of the concept. The new concept valve's 1st stage is an elongated plug profile with the annular passage developing an additional 10bar dynamic pressure loss above the typical 60 Barg back pressure when an inadvertent valve closing is initiated on a live train. This instigates a pump trip (by back pressure tripping at 70 barg) after start of the manual valve closing. The elongated plug annulus passage retains the valve opening and passing of any possible pressure surge following the pump trip for approximately 1 minute at the high pinion drive gear ratio prior to full closure against the valve seat. Figure 8 plots simulated pressure and flow surges of such a valve closure. The resultant pressure transient is completely mitigated as the initial pressure build-up response in the piping system initiates a earlier pump trip prior to full valve isolation. Any initially induced pressure transients pass through the annular passage of the valve trim into the back pressure piping system prior to full valve closure. Nevertheless, success of the above concept for this particular system is envisaged to be subject to the factors below:

1. Assumption that the time response of the BPCV is slow enough acting such that its pressure correction of the invoked back pressure generated by the modified manual isolator plug is limited;
2. Limit of its response to elevated back pressure set points at ~ 60 Barg i.e. will not generate sufficient back pressure to trip the Wirth Pumps at reduced back pressures;
3. An annular passage of 5mm clearance to invoke a back pressure of 10 Bar may be difficult to realise due to scaling to the plug or wear to the seat.

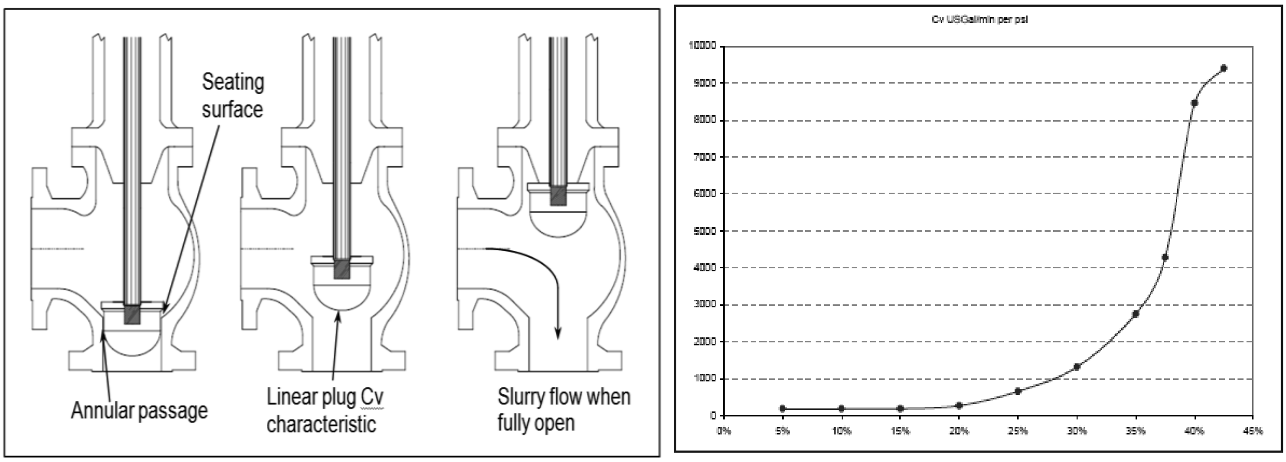

Figure 7 Conceptual Modified 2-Staged Plug Back Pressure Pipe Isolation Valve and Flow Characteristic Curve

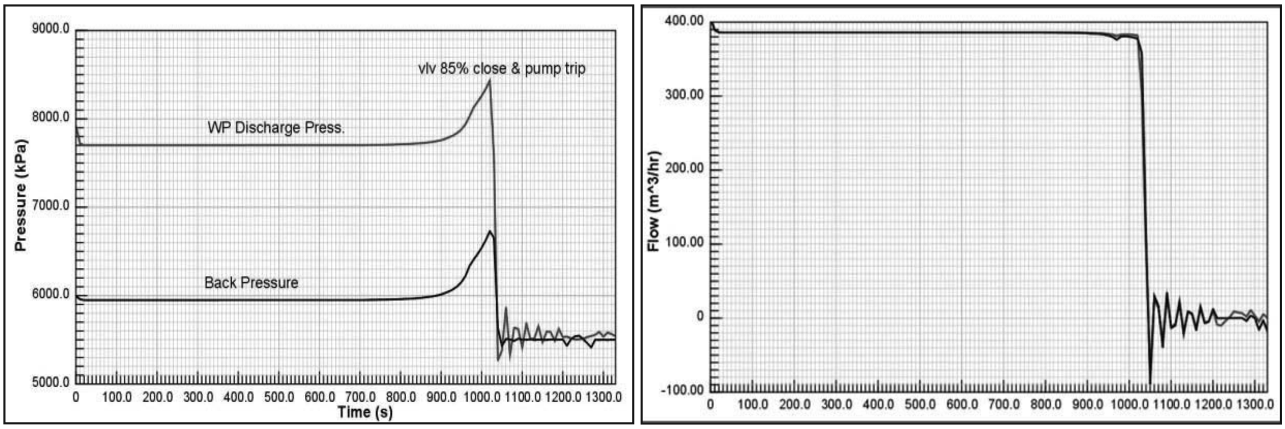

Figure 8 Predicted Elimination of Pressure and Flow Surge Using Modified 2-Staged Plug Valve

3. Conclusions and Recommendations

3.1 Conclusions

Mathematical numerical modelling of pressure transient events like ones in this paper, once calibrated with reliable plant data, shall serve as a good tool to explore a range of potential solutions for pressure surge mitigation of similar pumping/piping system. For this particular system, through extensive modeling of the pressure transients, it is concluded that peaks of the pressure surges resulting from the manual isolation valve shuts can be mitigated with various degrees of effectiveness via use of followings technical measures:

1. Increase of the existing air accumulator size and maintenance of good level control achieving maximum amount of air inside at all times;
2. Allocation of additional air accumulator immediately before the BPCV if permitted process wise;
3. Use of slow closing characteristics valve such as the conceptual modified 2-stage plug profile described in Section 2.4 to trip the pump earlier as well as avoiding dead heading the pump after occurrence of inadvertently valve closing;

In addition to the above "passive" mitigation measures, use of surge relief valves was also considered however not recommended for the application of this duty primarily because: 1)Time response of these devices as a function of the spring constant of the pressure relief device is too slow to mitigate the pressure wave (refer API 521 2007); 2)Scaling nature of the process slurry and requirement for frequent maintenance inspections limits the viability of the device such that when it is called upon to act, its full relieving capacity is not readily available.

Strict administrative procedures as well as abuse proof hardware/ instrument measures such as pad locks and proximity switches fitted to the valve are equally important to prevent pressure surges earlier even from source.

3.2 Recommendations

There is no single, simple and strictly passive protection system readily implementable to fully mitigate these pressure transients. The recommendations below are offered as a number of complementary systems presenting layers of overpressure protection (i.e. administrative, instrumented and mechanical), that when combined are deemed to offer a reasonable level of risk mitigation to such a complex problem.

1. All manual angle isolation valves inclusive and downstream of the holding tube manual isolator be fitted with locks as part of a strictly controlled administrative procedure.
2. All manual angle isolation valves inclusive and downstream of the holding tube manual isolator be fitted with proximity switches that should instigate a train pump trip upon closure.
3. The BPCV be modified with an actuator and shaft combination that prevent full closure of the valve.
4. The manual isolators be fitted with a proposed 2 staged linear profiled plug for trial in an attempt to sever the link between full manual valve closure and pump dead heading.

4. Acknowledgements

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