A Study of Pressure Safety Valve Response Times under Transient Overpressures

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Introduction

The work reports on research into pressure safety valves, which has been sponsored by members of an Energy Institute managed joint industry project to investigate the response of such valves to the pulse pressures which may arise during catastrophic tube failure in a shell and tube heat exchanger. The larger objective of this work has been to assess the circumstances in which safety valves may be used in place of bursting discs, reducing the risks associated with accidental disc failure.

A frequently encountered scenario in the operation of a shell and tube heat exchanger is that of high pressure gas on the tube side and liquid flowing through the shell, whose design pressure is rated at a much lower value. For example tube side pressures up to 200 barg and shell MAWP values in the range of 10 barg would be common. In the event of a tube rupture, the pressure relief device must be able to relieve the in-flowing gas volume at an equilibrium discharge pressure which meets the design guidelines (1,2). However, the pressure transient which precedes this equilibrium condition, can produce high pressures as a result of normal hydraulic, waterhammer effects and these transient events normally arise within a 5 - 20 msec period.

It is widely accepted that bursting discs have opening times within a few msec, and these are therefore commonly used to protect the shell from these transient pressure peaks. A disadvantage of using bursting discs however, is the irreversibility in their operation and the problems which this can cause. This can be a result of a short-term deviation in shell operating pressure, which is still within safe limits for shell integrity or back-pressure onto the disc emanating from the relief system. Incidents arising from such inadvertent disc operation have been reported and have prompted the present study into the timescales for safety valve operation, in order to exploit the advantages of the re-seating features of such valves.

Previous work has been particularly concerned with modeling and measuring the peak pressures generated as a result of tube failure in a shell (3) and subsequently with the performance of safety valves under transient condition (4,5). The latter studies reported on valves with up to an L orifice in size and using a 100mm ID water filled shock tube to provide the liquid environment for hydraulic wave transmission. In these studies, the effective tube rupture was created using the air filled driver of a normal shock tube, bursting an aluminium diaphragm and driving a bubble of air through various sizes of orifices ranging from 4 - 15 mm in diameter.

Depending on orifice size, peak incident pressure pulses at the valve location could be twice the set pressure of the valves and reflected pressures four times the set pressure. Limited information existed on the pressure-time history in the vicinity of the valve under such conditions and this earlier work indicated that pressure relief could arise with 4 - 5 msec for the valves tested.

The present initiative seeks to extend this work with the testing of larger valves which may be more consistent with the vessel and pipe sizes likely to be found in service, in particular in the upstream petroleum sector involving high pressure, high temperature production applications. Tests have principally involved a range of dynamic tests using an enlarged shock tube geometry and these have been supported with steady state flow rate tests of the valves before and after these dynamic tests. For the dynamic tests, incident pulse pressures have been chosen to be representative of the large transient hydraulic overpressures which can arise during a tube rupture.

Experimental method

Three valves have been tested in the project. These are defined as spring loaded safety valves of sizes 'M', 'N' and 'P', corresponding to relief areas of 3.6, 4.34 and 6.38 in^2 respectively. The set pressures for the M and N valves are 10 barg and for the P is 12.5 barg.

Static tests

The mass flow rates for the valves tested are typically in the range 60 - 130 kg/sec and a large water volume is required to provide a useful running time for static testing. This is provided by a $4m^3$ reservoir, shown in Figure 1. As can be seen, the relief valve is mounted vertically at one end and the top of the reservoir is provided with a pressurising air supply via a 75mm diameter line taking air from an adjacent high pressure receiver tank pressurised to 23 barg. The pressure applied during the tests is controlled manually by means of a gate valve on this supply line and the pressure applied during this procedure is held within approximately 1 bar of the set pressure.

The water reservoir is mounted on three load cells and the signals from these, as well as the reservoir pressure, are read to a data acquisition system reading at ten samples per second.

Figure 1. Reservoir used for valve testing under static conditions and showing M size valve in place.

Static discharge rates are measured before and after the transient pressure tests to determine any change in valve steady state performance.

Dynamic Tests

Dynamic testing has followed the approach adopted in the previous series of tests on the smaller valves.

A shock tube is used to create a pressure pulse within a water column and the incident pressure adjacent to the valve of interest is monitored to identify the timescale for the opening of the valve. The pressure pulse is created by the bursting of an aluminium diaphragm which seals a high pressure air reservoir connected to the water filled column. The connection is via a discharge orifice, and the combination of reservoir pressure and orifice area determine the pulse pressure amplitude which travels down the water column at the wave speed in the tube. For the materials used, this wave speed is around 1300m/s.

For this work, the diameter of the water column tube has been increased in order to provide a larger flow capacity to suit the larger valves being used. The air reservoir is monitored with a standard pressure transmitter and the water column is monitored using four piezoelectric pressure transducers (K1 - K4) and associated charge amplifiers. Data for all sensors are collected using Labview on a PC. During the operation of the tube, data are collected with a repeat interval of 20 μsec. Since much of the time of interest is within the first 15 msec, data are collected over a 240 msec period for each test. The raw data from each test are therefore the time resolved variations of the reservoir pressure sensor and the four piezoelectric sensors.

The overall schematic geometry of the shock tube is shown in Figure 2 and a photograph of the tube-end geometry in Figure 3. This indicates that the relief valve, located to the right end of the diagram, is oriented in the vertical position. Water discharge from the valve is unimpeded and exits the building via a 600mm diameter plastic collection tube.

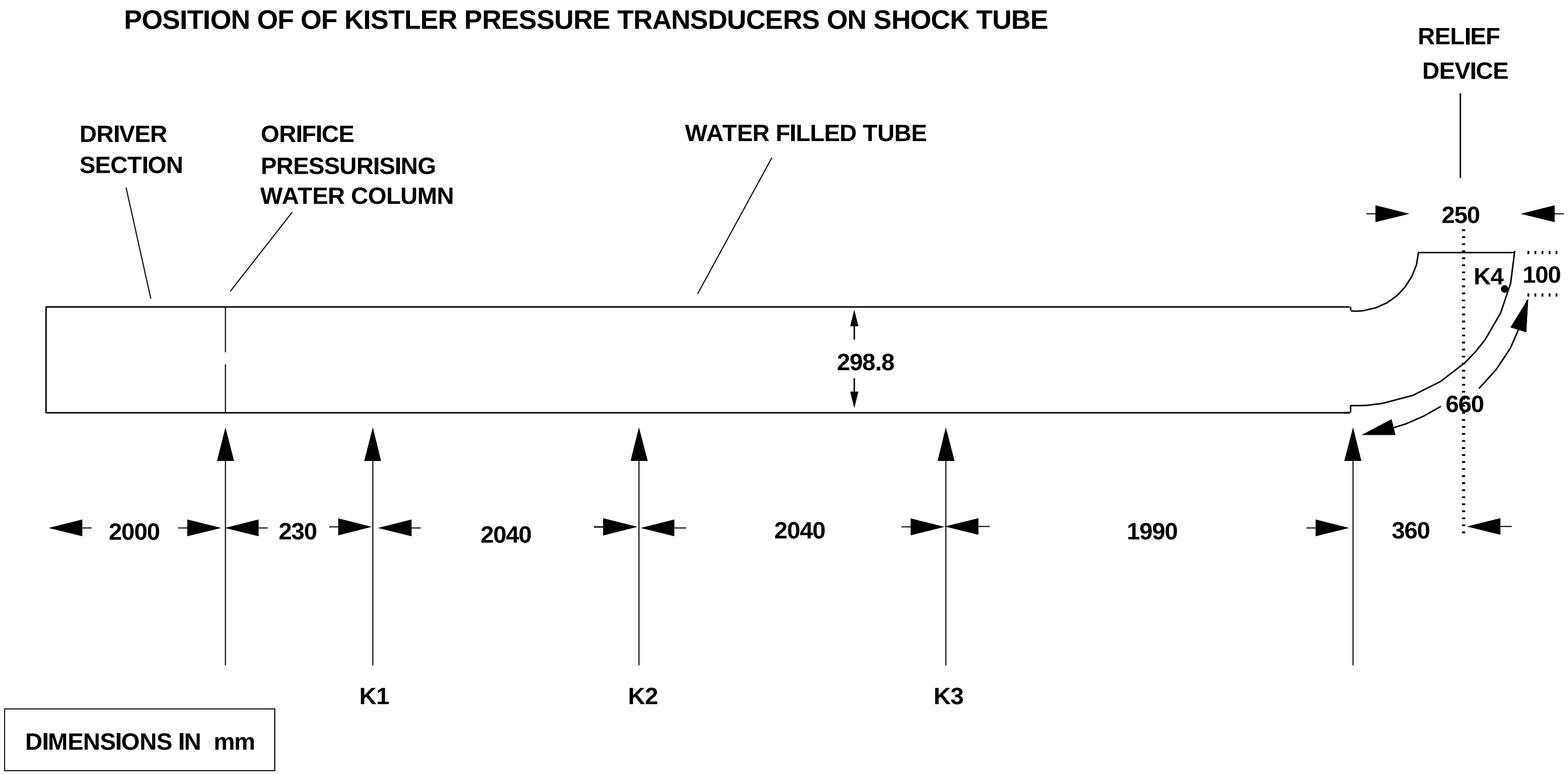

Figure 2. Overall schematic of shock tube indicating positions of 'driver', piezoelectric pressure sensors (K1 - K4) and relief valve for testing.

Figure 3. Relief valve (N) located at end of the water filled tube, also showing water outlet used for water filling and valve air bleed leg.

Based on previous results, the test programme for the three valves has set a range of target incident pulse pressures. These are indicated in Table 1 as well as their case identifiers for later reference. As can be seen, the maximum incident pulse pressure is aimed at being four times the set pressure.

The data capture are triggered by a signal appearing on K2, and some pre-triggered data are also collected to ensure that the K1 signal is captured as well as the reservoir pressure signal prior to the rupture of the aluminium diaphragm. The exact moment of diaphragm rupture is not under the control of the operator and is determined by the failure behaviour of the diaphragm being used. With this in mind, a series of pre-test calibration checks were carried out to establish the combination of diaphragm thickness and discharge orifice areas which would result in particular pulse pressures within the water filled column. This procedure is not exact and diaphragms tend to rupture over a range of applied reservoir pressures. However, the target incident pulse pressures identified in Table 1 are broadly achieved.

Operation of the tube involves:

- placement of the rupture diaphragm at reservoir exit and plastic seal over discharge orifice to contain water during filling
- filling of the water filled tube
- removal of air bubbles
- closure of inlet/outlet valves
- activation of the charge amplifiers
- pressurising of reservoir to the point of diaphragm rupture

Air bubble removal involves running water through the tube for around 20 minutes and bleeding of any air from the bleed points set up to remove any air traps within the system. The largest of these is the entry chamber to the relief valve which is at a dead end of the filling system. For this purpose, a vertically movable bleed leg is fixed within the elbow at the end of the tube and the open end of this leg is placed in contact with the valve seat during filling. When water flows from this bleed point the leg is closed and moved to a lower position.

Table 1. Target test conditions for dynamic testing, based on multiples of valve set pressure.

Valve type	Set pressure (barg)	Incident pressure pulse (barg)	Target pressure identifier
M	**10**	**12** **15** **25** **40**	**M 1.2** **M 1.5** **M 2.5** **M 4.0**
N	**10**	**12** **15** **25** **40**	**N 1.2** **N 1.5** **N 2.5** **N 4.0**
P	**12.5**	**15** **20** **30** **50**	**P 1.2** **P 1.5** **P 2.5** **P 4.0**

Results

Static tests

A sample trace showing the discharge and pressure behaviour for one of the valves is provided in Figure 4. The pressure curve shows the onset of valve opening, while the tank mass shows a fairly linear decrease with time over a 20 second period. Near the end of this period the gradient decreases and when this time point is compared with corresponding video footage, it is clear that air is also being expelled from this time onwards, i.e. a two phase mixture is being discharged. Discharge rates are therefore calculated using only the linear part of the curves for the valve characterisations. The performance data captures three parameters from these curves, opening pressure, mass flow rate (during constant mass flow period) and average applied pressure during the linear region.

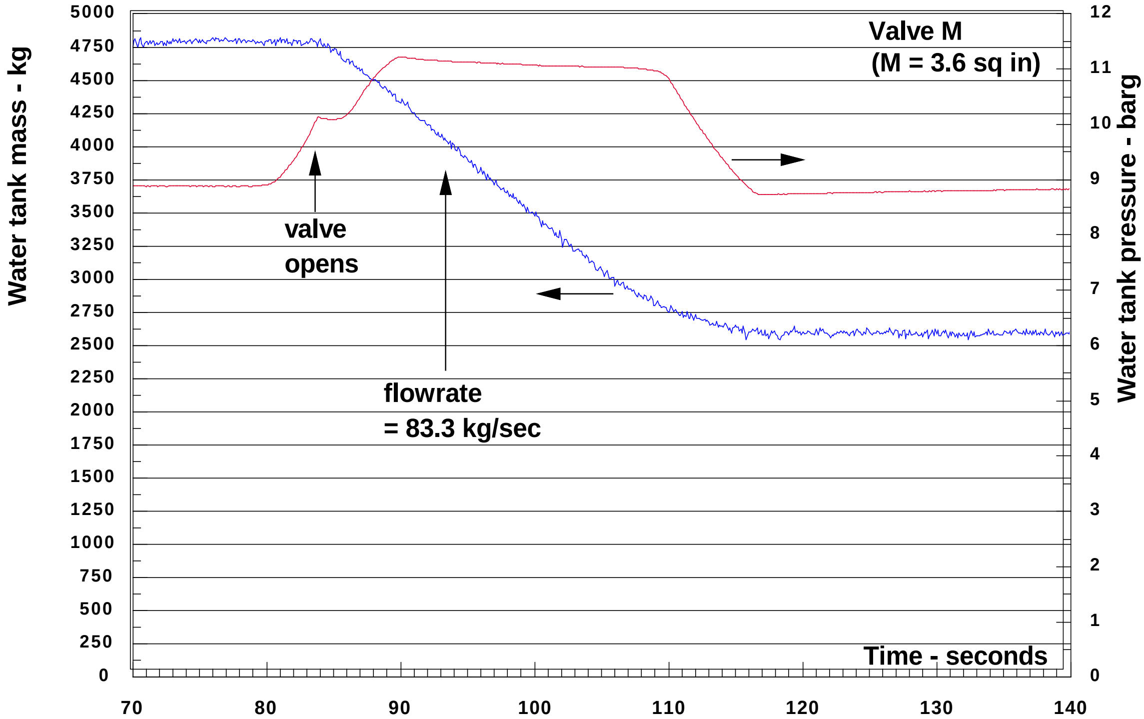

Figure 4. Example variation of water tank mass and applied tank pressure with time during valve discharge test.

Table 2 shows the data collected together from these tests. There is some small variation of opening pressures observed within each set and generally the mass flow rates measured increase with increasing pressure above the set pressure. It can be seen for all valves that the post-dynamic tests results are closely similar to those before dynamic testing and therefore the conclusion is that performance has been unaffected by these dynamic tests.

Table 2 Collected static test results for three safety valves, before and after dynamic tests.

Valve	Test ID	Before dynamic test			Test ID	After dynamic test		
		Valve opening pressure (barg)	Flow rate (kg/s)	Average applied pressure (barg)		Valve opening pressure (barg)	Flow rate (kg/s)	Average applied pressure (barg)
M	a	10.1	67.4	10.10	a2	10.1	85.9	11.27
	b	10.2	83.3	11.07	b2	10.1	86.7	11.07
	c	10.1	82.1	10.99				
N	a	10.5	108.7	11.47	a2	10.3	100.7	10.73
	b	10.7	100.9	11.31	b2	10.4	100.6	10.73
	c	10.4	101.1	11.21				
P	a	12.8	98.2	13.21	a2	12.8	91.2	13.1
	b	12.8	127.0	13.54	b2	12.8	100.6	13.1
	c	12.7	110.0	13.44				

Dynamic tests

The pressure traces for K1 - K4 contain some complex behaviour and these can be characterised by short term and long term behaviour. Taking Figure 5 as an example for the M valve (M 2.5b), where 0 msec corresponds to the instant of diaphragm rupture, an incident pressure pulse of around 30 barg develops and propagates down the water filled tube. There can be seen pressure rises on K1 to K4 at different time positions corresponding to the transit delays to the transducers of the pulse. K4 shows an almost doubling of the pulse as it reflects from the closed valve position followed by a decay as the valve opens.

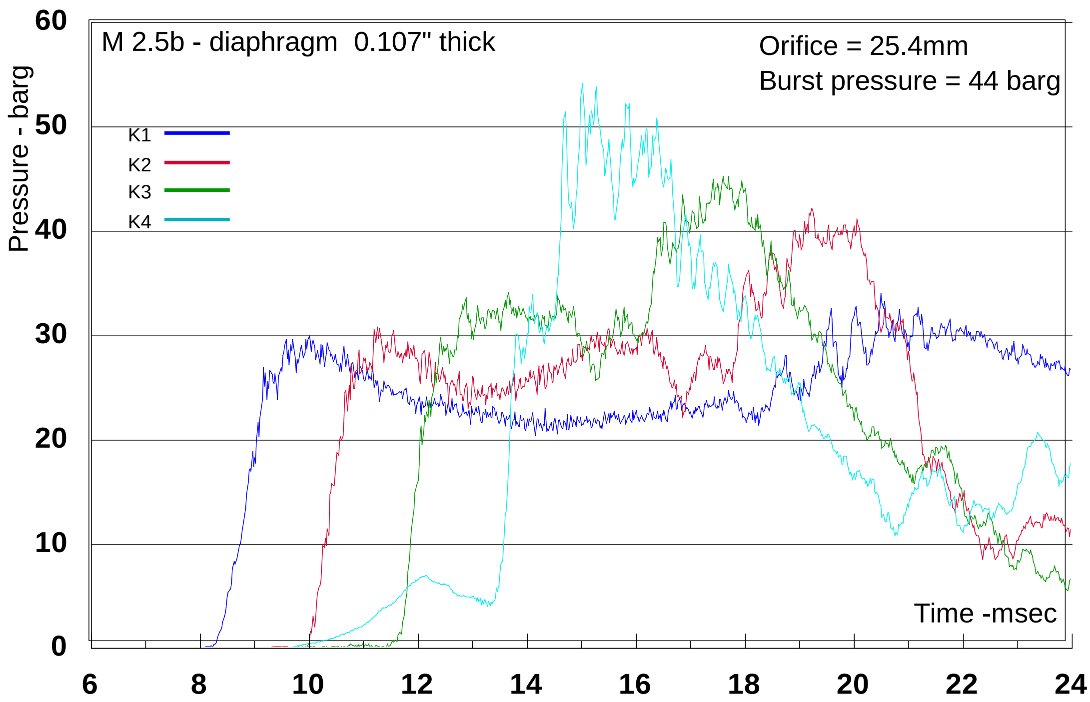

Figure 5. Pressure traces on K1 - K4 as initial pressure wave develops along water filled tube following upstream diaphragm rupture, Diaphragm burst pressure and orifice discharge diameter are indicated.

Figure 6 shows the longer term behaviour of the pressure as the oscillations in valve opening and closing quickly decay to a pseudo-steady discharge condition.

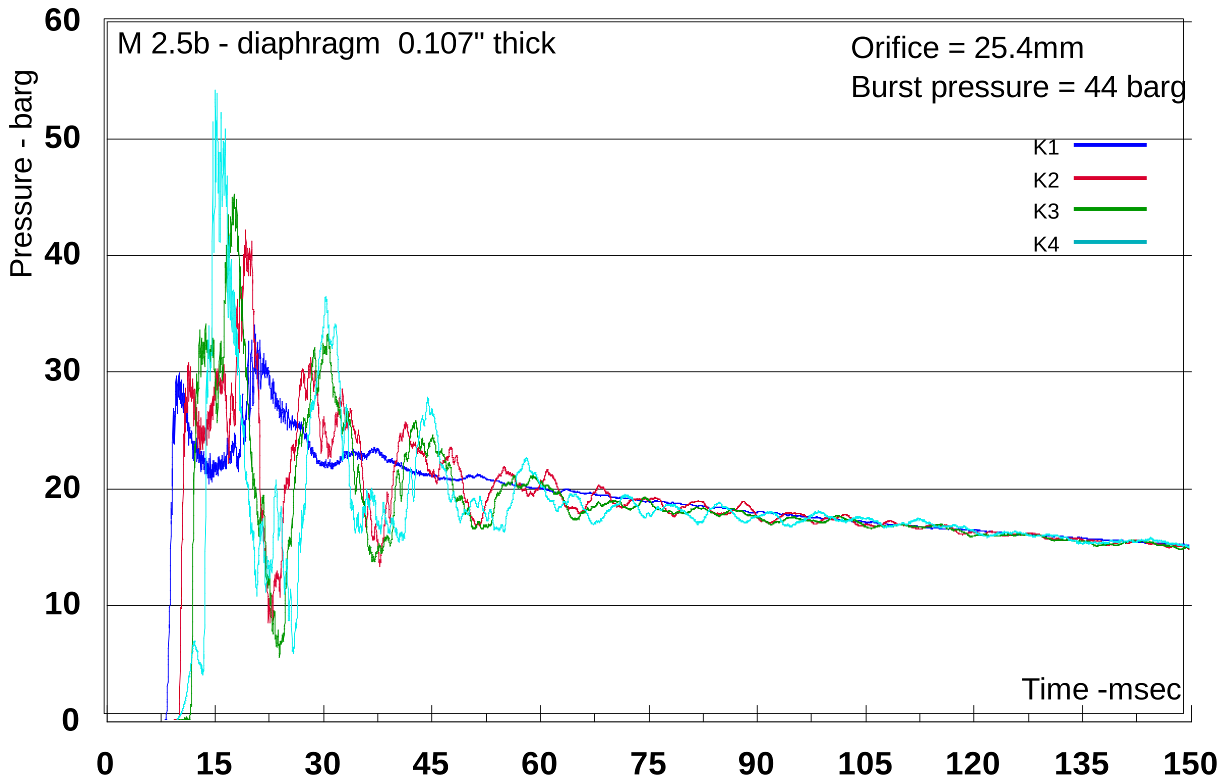

Figure 6. Long term pressure wave behaviour leading to steady valve discharge.

These pressure behaviours are typical of that for all of the valves tested under the range of pressures noted above.

The time delays in combination with the transducer separations correspond to a wave speed close to 1300 m/s. A key feature of the piezoelectric pressure traces is the reflected pressure wave behaviour, first seen on K4 and later on K3 and K2. This reflected pressure at K4 is the effective drive pressure for the opening of the valve.

Returning to Figure 5, an anomalous feature on the K4 trace is the initial rise in pressure starting at 9 msec and peaking around 6 barg at 12 msec. Investigation of this feature showed it to be due to a slight movement of the tube as the upstream aluminium diaphragm ruptures giving rise to a temporary pressure fluctuation at K4.

Following the initial pressure rise on K4, the pressure peaks and falls as the valve opens. As the pressure falls to the set pressure the valve begins to close again, after which the pressure will rise again and the relief process repeats. Of particular interest is the timescale for the initial pulse to rise and fall as this is uniquely connected with the valve response behaviour. In previous work the valve opening was modeled and the resulting pressure traces were reproduced using a characteristic valve response time. From that work it was clear that the valve response time was close to the rise and fall time of the initial pulse on K4 and for the present reporting, this measure has been extracted from the recorded pressure data.

This is explained with reference to Figure 7, where the measured rise and fall time (RFT) is taken as that time between the point at which the set pressure is initially exceeded and when the pressure returns to the set pressure after valve opening. In some cases the pressure drops to a minimum that is above the set pressure , in which case the time at the minimum is taken.

This present paper presents these values of the RFT for all of the cases of Table 1.

Each of the twelve conditions shown in Table 1 is repeated between two and four times

The RFT values for the full set of data are shown in Table 3, where the case identifiers relate to those shown in Table 1.

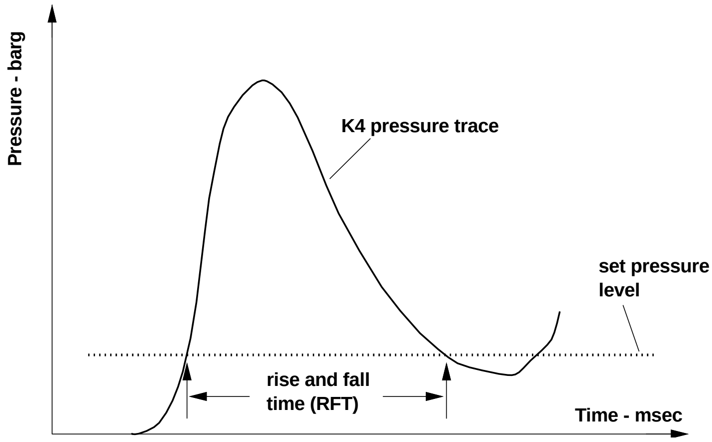

Figure 7. Schematic showing the extraction of the rise and fall time from the K4 pressure trace.

Table 3. Time response data for valve dynamic testing using shock tube generated pulse pressures.

Valve/target pressure[1]	Case identifier	Peak reflected pressure (barg)	RFT (msec)
M 1.2	a	27.5	6.4
	b	28.0	5.9
M 1.5	a	36.0	6.8
	b	37.0	6.2
	c	37.5	6.5
M 2.5	a	65.0	7.7
	b	54.0	7.1
	c	56.0	7.7
M 4.0	a	67.5	7.1
	b	70.0	7.2
	c	74.0	7.1
N 1.2	a	35.0	7.0
	b	27.5	6.5
	c	27.0	6.3
N 1.5	a	36.0	6.2
	b	36.0	6.4
	c	38.0	6.3
	d	33.0	6.9
N 2.5	a	51.0	7.6
	b	51.0	7.6
	c	53.0	7.6
N 4.0	a	60.0	7.3
	b	68.0	6.9
P 1.2	a	35.0	6.8
	b	36.0	6.7
	c	35.0	6.7
P 1.5	a	44.0	6.7
	b	40.0	6.6
	c	40.0	6.2
P 2.5	a	52.0	7.2
	b	52.0	6.6
	c	52.0	6.7
P 4.0	a	80.0	7.8
	b	80.0	7.8

Note 1 Valve identifier, e.g. M 1.2, refers to valve M with an incident pressure 1.2 times the set pressure. RFT is the rise and fall time of the incident pulse pressure recorded at K4 as depicted in Figure 7.

Discussion

The preliminary conclusions for the work carried out to date indicate that, despite the large excess pressure applied to the valves during dynamic testing, relief performance during normal steady state operation seems little affected.

Previous work on smaller valves e.g. size L, indicated that pressure decay on valve opening could be modeled using valve response times in the range 4 - 6 msec over a range of excess pressures similar to the present work. The rise and fall times measured for all of the valve tests in the present work indicate that most of these are in the range 6 - 8 msec. This is also found to be the case even for the lowest of the pressure pulses applied, and is likely to arise from the pressure doubling effect on wave reflection from the closed valve seat, meaning that even for these low pressure cases, the effective opening pressure is around 2.5 times the set pressure.

The issue of heat exchanger tube rupture within low pressure shells has been addressed only intermittently since the 1990's and studies have sought to predict the peak pressures and time durations which the shell is exposed to. The assumption has been that bursting discs will protect the shell against short term high pressure transients as a result of their short rupture times. As early as 1972 (6) disc rupture times have been taken as 0.6 msec and these values have since been confirmed through industry studies such as ref (5).

A more comprehensive analysis carried out by Cassata et al (7) sought to examine the shell pressure and time duration exposure using a relief device with an opening time of 5 msec. It is recognised by such studies that local high pressure exposure is inevitable due to pressure wave reflection and the assumption has been that this is more likely to be serious when the exposure extends to the full circumference of the shell, since this pressure distribution is compatible with the breathing distortion of the shell experienced during static hydro-tests. The outputs from the Cassata study on a shell with a MAWP of 10 barg showed that shell pressure around the rupture was 65 barg for the tube pressure of 258 barg used, for locations close to the relief point pressure pulse widths were in the range 5 - 10 msec and for locations distant from the relief point were 5 - 20msec.

It is clear that shell exposure to overpressure results from the interplay between several factors including tube pressure, tube to shell diameter ratio, relief device opening times and locations, and furthermore that the response of the shell is expected to be a function of the space and time distribution of pressure as well as its own geometry factors. Current fluid-structure interaction models have the capability of exploring this time dependent interaction and the results presented for the response of the relief valves tested provides new and valuable base data for use with such models. The ultimate goal of such a modeling approach, and the Energy Institute JIP, will be to determine the range of options available in choosing relief devices which maintain the safety of the shell whilst minimising the effect of minor deviations in operating system pressures. Going forward, an extension to ref. (3) will include the findings of such an analysis, like key factors, so as to guide future design.

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