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Experimental values for adjusting an automatic control valve in gas pipeline transportation

Authors

Mehdi Mahmoodi [a]*
Mofid Gorji Bandpy [a]

[a] Babol Noshirvani University of Technology, Babol, Iran

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ABSTRACT

When a natural gas pipeline ruptures, the adjacent automatic line control valves (ALCVs) should close quickly to prevent leakage or explosion. The differential pressure set point (DPS) at each valve location is the main criteria for value setting in ALCV action. If the DPS is not properly adjusted, the ALCV may mistakenly close or it may not take any action at proper time. This study focused on the DPS values prediction for setting ALCV installed on a gas pipeline with 1mm orifice diameter. The effect of characteristic parameters such as pipeline operational pressure (POP) and pipeline pressure drop rate (ROD) due to rupture or major leak was experimentally investigated on DPS. Twenty-five different conditions with double set of typical mentioned characteristic parameters were chosen. For each condition, the differential pressure (DP) was measured over 180 seconds by analyzing the experimental values. Therefore, 25 maximum DP values (DPSs) were obtained. The DPS increases by increase in ROD or decreasing POP parameters. Because of using nitrogen gas instead of natural gas due to safety reasons, the DPS results can be practically applied by adding a safety factor of 15%. The diagram of DPS with respect to ROD and non-dimensional DPS (DOP) versus non-dimensional ROD (RTP) was provided for different POPs.

Keywords: Automatic Control Valve, Operating Pressure, Adjusting Values, Pressure Drop Rate, Gas Pipeline.

1. Introduction

Natural gas is one of the most important energy sources in the world and has an important role in industry and economy sections. Natural gas transportation and distribution are generally done in all nations through the gas pipelines network. Construction of new pipelines among countries will increased. Natural gas supplies almost one-fourth of all energy used in the world [1]. Leak detection systems are a major element in the design and development of ALCVs installed on gas transportation pipelines and it is hard to overestimate their contribution in ALCVs performance. Most of these pipelines are passed through forests, lakes and crowded cities. Rupture, explosion or large leak due to various reasons are hazardous problems affecting the safe operation of pipelines. Leak detection in pipeline systems carrying natural gas and other petroleum products is so serious from economic, environment and safety aspects point of view. ALCVs are widely installed on oil and gas pipelines, petroleum, chemical industry and nuclear power industries for these aspects [2-3]. When a natural gas

* Corresponding author: Mehdi Mahmoodi
Babol Noshirvani University of Technology, Babol, Iran
E-mail address: mehdymahmoody@gmail.com

pipeline ruptures, the automatic control valves should close quickly to prevent significant gas leakage because the rupture will cause a disastrous accident.

Various experimental studies for leak detection in liquid pipelines have been performed but relatively fewer studies for gas pipelines have been presented [4-5]. Several studies on leakage and ruptures detection in gas pipelines have been reported [6-9]. However, there are only a few studies on adjusting the differential pressure set point (DPS) values of automatic line control valves (ALCVs) especially about how the value settings might differ between gas pipelines. General curves for few conditions of ALCV were obtained by Lorusso [10]. The ALCV setting values based on ROD for gas pipe burst condition with block valve type were reported [11]. Experimental test values for finding DPS values to adjust a quarter-turn actuator in gas transportation pipeline simulator were presented with different test setup [12]. Setting of ROD values for automatic line-break control valves in natural gas pipelines was numerically studied [13-14].

The DPS value is an important parameter that determines whether an ALCV closes in time or not. Due to the changing operating conditions along a pipeline, calculation of DPS values for ALCVs is complex. The DPS values are usually adopted based on experiences. Due to great sensitivity on the rate of pressure variation over time in different pipeline conditions, the ALCV requires detailed and accurate setting [15]. The normal pressure drop rate is due to frictional losses in a piping system. The normal pressure drop should not cause the ALCV to act. Actually, the differential pressure value between two sides (right and left) of diaphragm valve (Figure 1) is DP. When DP value equals DPS, the diaphragm moves to right and change normally closed valve position. ALCV will be regulated with certain DPS for different conditions. DP value depends on several parameters such as pipeline operating pressure (POP) and rate of pressure drop due to rupture or large leak (ROD). The orifice diameter (Figure 1) is another important parameter of ALCV. The orifice diameter is constant in this study. It is equal to 1 mm. As mentioned, the DPSs of ALCV are usually adopted based on experience or estimated values derived from pipeline steady flow over a long time.

In this study, the effects of critical parameters such as POP and ROD on DPS of ALCV were experimentally studied. Understanding the effects of these parameters is critical to design and regulate ALCVs. The 25 different conditions were chosen by changing mentioned parameters. Each condition was experimentally studied 3 times, thus 75 tests were performed. The DP over 180 s was depicted for each condition by statistical analysis of the experimental values. Therefore, 25 DPSs with their occurrence times (t_{max}) were obtained. A series of equations for the DP value prediction were developed. These equations were validated over 180 s for different available conditions. Uncertainty analysis was also performed and finally, a series of equations relating the DOP to the RTP for different POPs were developed. Extracting new accurate correlations for predicting ALCV adjusting values in engineering application and investigating more effective parameters on ALCV performance are the motivations of this paper.

2. Experimental Facilities and Setup

The schematic of experimental test setup is illustrated in Fig.1. The facilities used in this study are shown in Fig.2. The pressure of gaseous fluid is transferred from pipeline to ALCV through connecting hose and tube (No.10 in Fig.3). This is divided into three branched tube routes. Route 1 is through the normally closed valve.

The test setup is shown in Fig.2 and contains; (1) pipeline, (2) compressed nitrogen cylinder, (3) pressure gauge, (4) pressure diaphragm valve, (5) electrical box, (6) PT signals receiver, (7) pressure transducer (PT), (8) set of orifice and check valve, (9) reference tank, (10) tubing (11) calibrated valve, (12) connecting hose. A closed ends pipe was used as pipeline in this experimental setup (No.1 in Fig.2). In order to avoid any hazardous conditions or catastrophic explosion, nitrogen gas was used instead of natural gas. The pipeline pressure is attained to the desired POP by a compressed nitrogen cylinder (No.2 in Fig.2) via connecting hose.

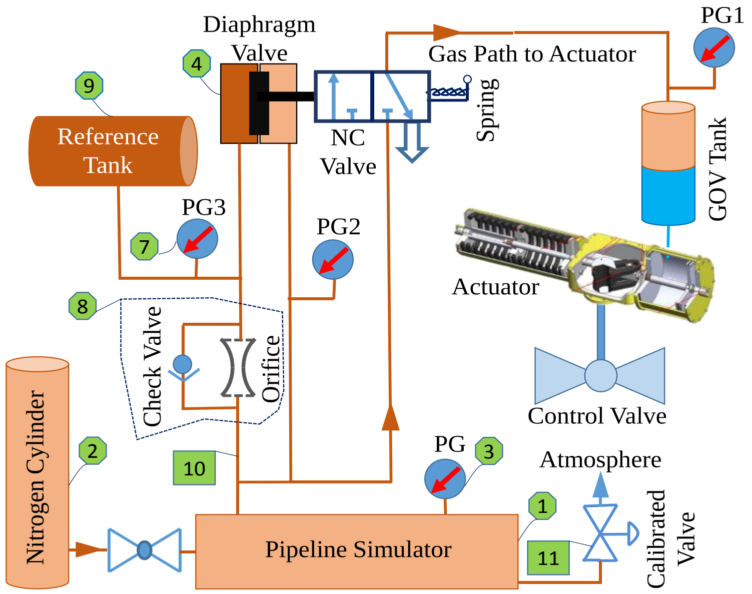

Fig. 1. Experimental setup scheme

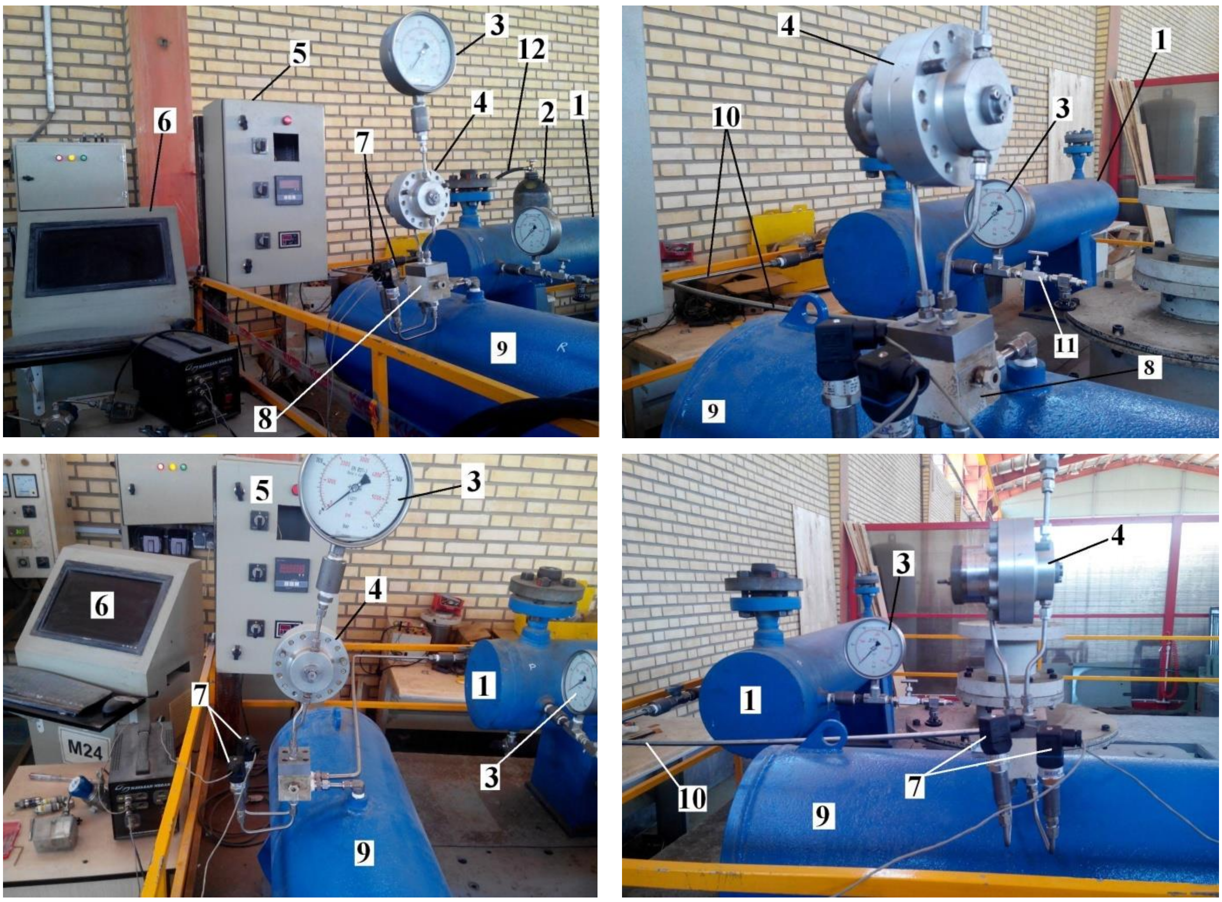

Fig. 2. Experimental test setup scheme

The valve on cylinder is closed when all routes in Fig.1 have the same pressure as POP. Pressure gauges in Fig.2 are not used for data acquisition. A calibrated valve (No.11 in Figure 2) is attached to the pipeline to create a ROD by withdrawing compressed nitrogen gas to the atmosphere for 180 s. Nitrogen gas goes to the reference tank by a set of orifice and check valve (No.8 in Fig.2) installed in Route 3 (Fig.1). The fluid especially chooses the route with check valve instead of orifice because of the lower pressure drop. The pressure of the reference tank equals pipeline pressure, instantaneously. When a failure occurs in pipeline, the reference tank pressure is greater than pipeline pressure. Now, the route with check valve is closed. Therefore, all the fluid in reference tank passes through the orifice. This creates new pressure drop rate in the system which is lower than the ROD. The DP between pipeline and reference tank equals the DP between two sides of the diaphragm valve. The normally closed valve position changes when the DP attains maximum value (DPS) at the time of t_{max} and ALCV acts finally.

Isolated pipeline is pressurized to a constant value and then the pressure is reduced for 5 minutes by opening the valve (No.11 in Figure 2) which is installed on the pipeline. The mean ROD (kPa/s) should be measured for this determined valve opening (in degree). To calculate the ROD, the pressure difference (kPa) between the initial time and 5 minutes after valve opening was divided to 300 seconds (test time duration). Therefore, the ROD has been obtained for this determined valve opening. This procedure was repeated 3 times for this determined valve opening to obtain the mean ROD value. Consequently, the valve calibration was performed by 48 tests (16 ROD× 3 times repetition) for all conditions. Finally, the valve was calibrated for 9 ROD values from 0.2 up to 4.2 kPa/s. The pressure transducers (No.7 in Fig.2) were calibrated by a Yantrika hydraulic dead weight tester. Cables and amplifier uncertainties are negligible. Twenty-five different typical conditions were summarized in Table 1 based on 5 different values for the POP and 16 different values for the ROD. Each condition was experimentally studied 3 times, thus 75 experimental tests were performed. Maximum and minimum limits of each ROD range depend on POP and chosen orifice diameter in ALCV. Therefore, 25 DPSs with their occurrence times were obtained.

The equipment used in this study are listed with their uncertainties and measured parameters in Table 2.

3. Results and Discussion

As mentioned above, DPS can be determined according to the maximum DP values over 180 s. Twenty-five different conditions were performed based on the parameters shown in Table 1. Failure due to rupture occurred at initial time (t=0) and its pressure drop rate is equal to ROD. The DP increased with respect to time to a maximum value (DPS) and then it decreased for all conditions. The DP with respect to time is depicted based on transmitted data by two pressure transducers (PG2 and PG3) for 180 s after line-failure for each condition as shown in Figs. 3 to 7. DP has been measured every 10 s. For example, 270 DP values (5 conditions×18 measured data in each condition×3 times) have been measured in Fig.3. In fact, this is the result of intrinsic behavior of the orifice and check valve set (No.8 in Fig.2) in ALCV. The DP is determined as a function of ROD and POP

Table 1. Experimental parameters and their values

Parameter	Unit	Values
POP	kPa	3500, 5000, 7500, 9000, 10500
ROD	kPa/s	0.2, 0.8, 1.4, 1.8, 2.2, 2.8, 3.2, 3.6, 4, 4.6, 5.4, 5.8, 6.2, 6.6, 7.2, 8

Table 2. Equipment and their uncertainties

Equipment and Model	Accuracy	Test Range	Uncertainty
Digital Stopwatch (Sigma-Aldrich, Germany)	± 0.003%	0-180 s	± 5.4×10^{-3} s
Pressure Transducer, PXM01MD0-160BARG5T (Omega, UK)	± 0.05%	2060-10500 kPa	± 0.22%

parameters. The DP values are predicted by Eq.(1) over 180 s for all conditions. Each condition has its six unique constant coefficients such as *a, b, c, d, e* and *f*. These six constant coefficients are shown in Tables 3, 5, 7, 9 and 11 for each condition. In fact, these coefficients are unknown functions of ROD and POP.

$$\mathrm{DP} = \mathbf{a}e^{\mathbf{b}\sqrt{t}} + \mathbf{c}\mathrm{Ln}\left(1+\mathbf{d}\sqrt{t}\right)+\mathbf{e}\sqrt{t}+\mathbf{f} \quad (1)$$

Each row in this table is the result for each condition after 3 times repetition. For data x_i, deviation is defined by d_i (Eq.(2)). For a sample size n, data's mean ($\bar{X}$) is calculated by Equation 2. Standard deviation (SD) depends on least squares fitting and is calculated by Eq.(3). Maximum and mean values of SD are reported. Error bars are depicted based on SD in Figs. 3 to 7. For parameter x, uncertainty of experimental test repetition and uncertainty of its measuring equipment are shown by U_{rep} and U_{tool}, respectively. The half measuring equipment accuracy is h_a in Eq.(4). Total uncertainty of each experimental test (U_{tot}) is defined by Eq.(4). Maximum and mean values of total uncertainty in DP measurements for any condition are reported.

$$\bar{X} = \sum_{i=1}^{n} x_i/n;\ d_i = x_i - \bar{X};\ \sum_{i=1}^{n} d_i = 0 \quad (2)$$

$$SD = \sqrt{\sum_{i=1}^{n} d_i^2 \Big/ (n-1)} \quad (3)$$

$$U_{tot} = \sqrt{U_{tool}^{\ 2} + U_{rep}^{\ 2}} = \sqrt{h_a^{\ 2}/3 + \sum_{i=1}^{n} d_i^{\ 2} \Big/ n\,(n-1)} \quad (4)$$

Mean and maximum values of standard deviation were 1.68 and 3.2 kPa, respectively. Mean and maximum values of DP estimation error were 1.34 and 19%, respectively. Mean and maximum values of DP total uncertainty were 0.98 and 1.85 kPa. Mean estimation error of t_{max} is 2.42% for 3500 kPa POP.

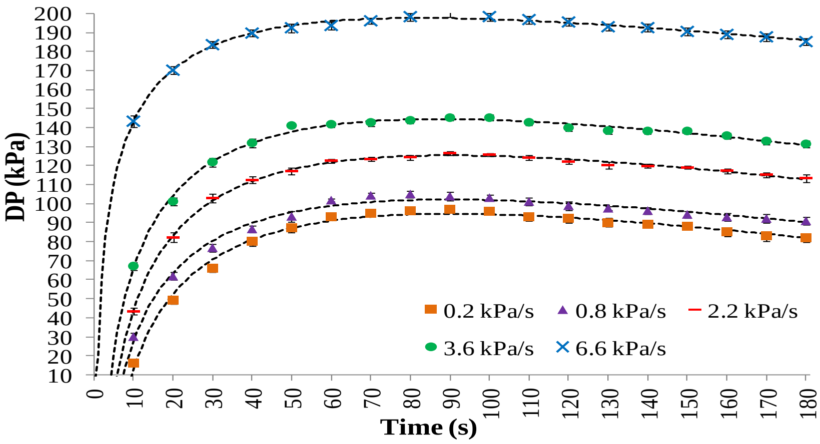

Fig. 3. DP versus time for 3500 kPa POP

Table 3. Coefficients in Eq.(1) for 3500 kPa POP

ROD	a ×10^{-3}	b ×10^{-6}	c ×10^{-2}	d ×10^{-3}	e ×10^{-1}	f ×10^{-3}
0.2	1.57	-2.84	1.89	1.92	-1.99	1.57
0.8	1.43	-2.84	1.74	1.94	-1.83	-1.43
2.2	1.54	-2.84	1.89	1.99	-1.99	-1.54
3.6	1.49	-2.84	1.86	1.93	-1.98	-1.49
6.6	0.99	-2.84	1.35	1.97	-1.49	-0.99

Table 4. t_{max} for 3500 kPa POP

ROD	0.2	0.8	2.2	3.6	6.6
Estimated Value	91	90	91	88	83
Estimation Error %	1.1	0	1.1	2.2	7.7

The percent error of DP estimation is defined using Eq.(5). For any condition, estimated value of DP is in good agreement with its obtained experimental value.

$$\text{Estimation error }\% = \left|\text{Estimated value} - \text{Experimental value}\right| / \text{Experimental value} \times 100 \quad (5)$$

According to the experimental tests, the required time to attain maximum DP (t_{max}) is 90 seconds. The estimated value of t_{max} is calculated by solving Eq.(6) which is a derivation of Eq.(5). The estimated values of t_{max} and their errors are presented in Tables 4, 6, 8, 10 and 12 for each condition.

$$\mathbf{ab}e^{\mathbf{b}t} + \frac{\mathbf{cd}}{\left(1+\mathbf{d}\sqrt{t}\right)} + \mathbf{e} = 0 \quad (6)$$

When the POP is constant, the only variable parameter is ROD. The increase of ROD causes an increase in DP for other constant parameter (POP) for all conditions. More mass of compressed nitrogen gas in the pipeline ($\dot{m}_{PL}$) is discharged to the atmosphere by increasing the ROD. The pressure of ALCV equals the pipeline pressure at the initial time before pipeline failure. The pressure drop rate on the right side of the diaphragm valve (Fig.1) equals the ROD because of the direct connection. The pressure drop rate on the left side of it differs from the ROD because of the compressed nitrogen gas passing through the orifice.

Mean and maximum values of standard deviation were 1.84 and 2.81 kPa, respectively. Mean and maximum values of DP estimation error were 1.23 and 12%, respectively. Mean and maximum values of DP total uncertainty were 1.08 and 1.62 kPa. Mean estimation error of t_{max} is 2.86% for 5000 kPa POP.

Table 6. t_{max} for 5000 kPa POP

ROD	0.2	1.4	3.2	4.6	7.2
Estimated Value	88	92	91	89	83
Estimation Error %	2.2	2.2	1.1	1.1	7.7

The $\dot{m}_{PL}$ is always equal or greater than the discharged mass flow rate of the reference tank ($\dot{m}_{REF}$). The $\dot{m}_{PL}$ value increases by increase in ROD. In fact, the difference between $\dot{m}_{PL}$ and $\dot{m}_{REF}$ is increased, which consequently increases the DP. This DP increases to a maximum value (DPS) and then decreases due to the mass reduction of compressed nitrogen gas inside the reference tank, so finally, the pressure of reference tank approaches the pipeline pressure.

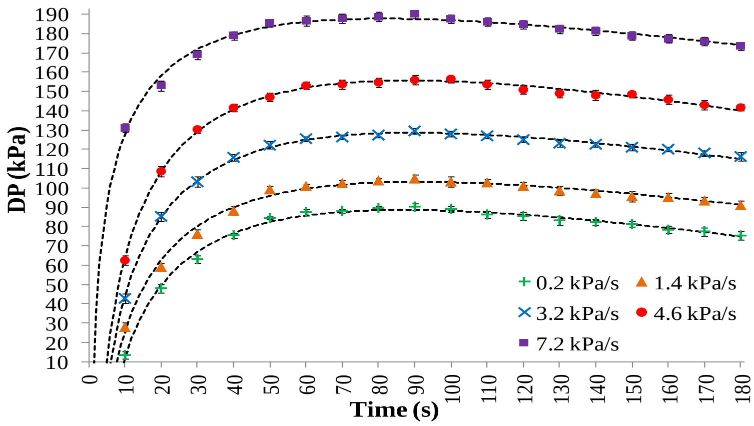

Fig. 4. DP versus time for 5000 kPa POP

Table 5. Coefficients in Equation 1 for 5000 kPa POP

ROD	a ×10^{-3}	b ×10^{-6}	c ×10^{-2}	d ×10^{-3}	e ×10^{-1}	f ×10^{-3}
0.2	1.52	-2.84	1.83	1.93	-1.96	-1.52
1.4	1.48	-2.84	1.8	1.93	-1.89	-1.48
3.2	1.61	-2.84	1.98	1.91	-2.09	-1.61
4.6	1.75	-2.84	2.17	1.9	-2.31	-1.75
7.2	1.13	-2.84	1.51	1.96	-1.67	-1.13

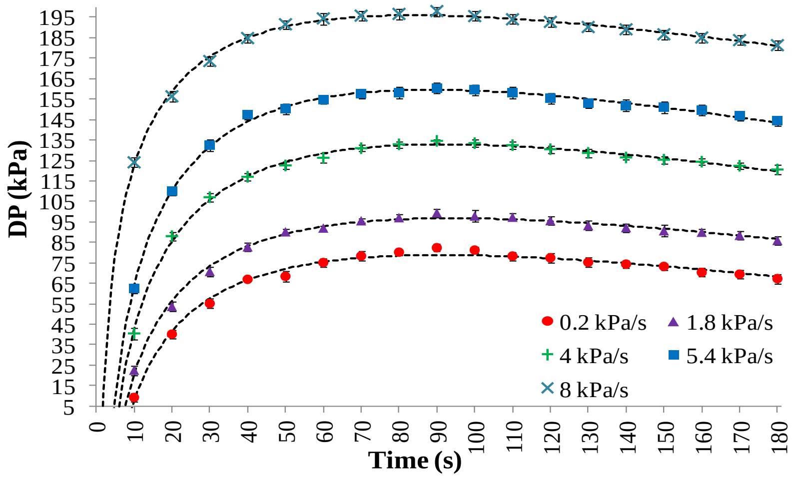

Fig. 5. DP versus time for 7500 kPa POP

Table 7. Coefficients in Equation 1 or 7500 kPa POP

ROD	$a \times 10^{-3}$	$b \times 10^{-6}$	$c \times 10^{-2}$	$d \times 10^{-3}$	$e \times 10^{-1}$	$f \times 10^{-3}$
0.2	1.37	-2.84	1.64	1.95	-1.72	-1.37
1.8	1.42	-2.84	1.72	1.94	-1.77	-1.42
4	1.69	-2.84	2.07	1.91	-2.16	-1.69
5.4	1.83	-2.84	2.26	1.89	-2.41	-1.83
8	1.39	-2.84	1.8	1.94	-1.97	-1.39

Table 8. t_{max} for 7500 kPa POP

ROD	0.2	1.8	4	5.4	8
Estimated Value	93	95	93	90	85
Estimation Error %	3.3	5.6	3.3	0	5.6

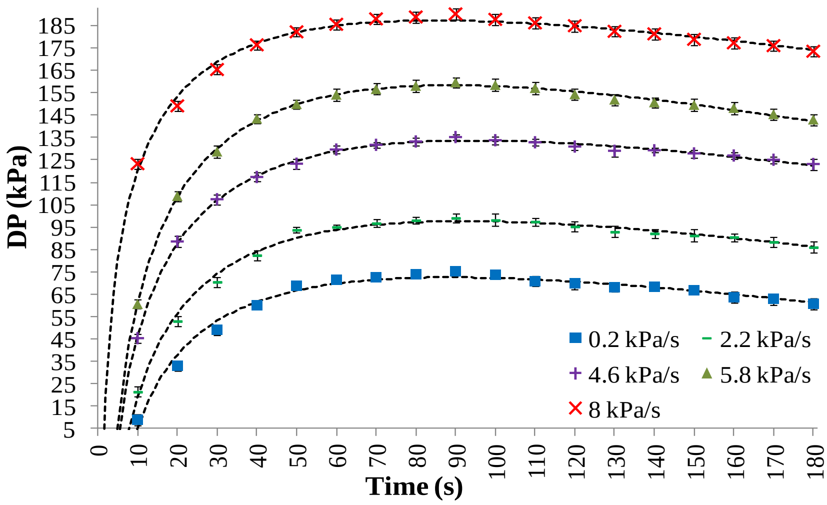

Fig. 6. DP versus time for 9000 kPa POP

Mean and maximum values of standard deviation were 2.01 and 2.81 kPa, respectively. Mean and maximum values of DP estimation error were 1.33 and 22%, respectively. Mean and maximum values of DP total uncertainty were 1.18 and 1.62 kPa. Mean estimation error of t_{max} is 3.56% for 7500 kPa POP.

Mean and maximum values of standard deviation were 2 and 2.9 kPa, respectively. Mean and maximum values of DP estimation error were 1.78 and 43%, respectively. Mean and maximum values of DP total uncertainty were 1.17 and 1.68 kPa. Mean estimation error of tmax is 2.88% for 9000 kPa POP.

Table 9. Coefficients in Equation 1 for 9000 kPa POP

ROD	a ×10^{-3}	b ×10^{-6}	c ×10^{-2}	d ×10^{-3}	e ×10^{-1}	f ×10^{-3}
0.2	1.32	-2.84	1.58	1.95	-1.68	-1.32
2.2	1.49	-2.84	1.8	1.93	-1.87	-1.49
4.6	1.59	-2.84	1.95	1.92	-2	-1.59
5.8	1.84	-2.84	2.28	1.89	-2.42	-1.84
8	1.25	-2.84	1.63	1.95	-1.77	-1.25

Table 10. t_{max} for 9000 kPa POP

ROD	0.2	2.2	4.6	5.8	8
Estimated Value	90	93	96	90	86
Estimation Error %	0	3.3	6.7	0	4.4

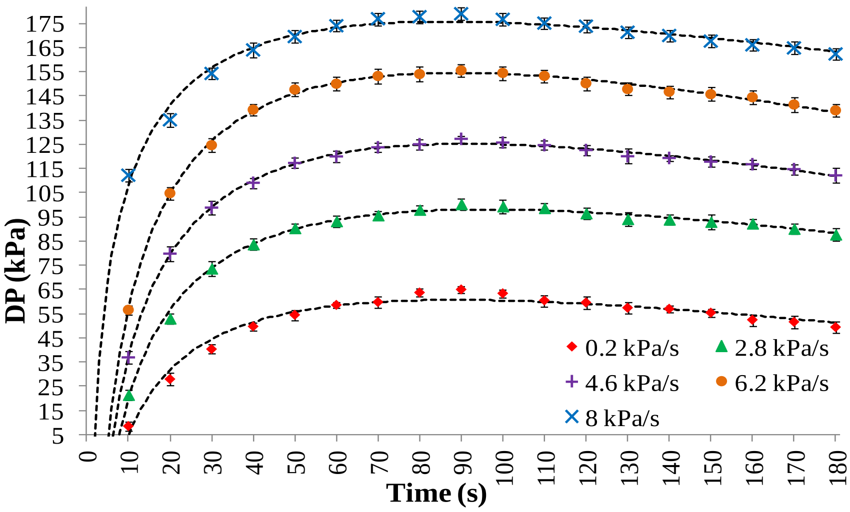

Fig. 7. DP versus time for 10500 kPa POP

Table 11. Coefficients in Equation 1 for 10500 kPa POP

ROD	a ×10^{-3}	b ×10^{-6}	c ×10^{-2}	d ×10^{-3}	e ×10^{-1}	f ×10^{-3}
0.2	1.1	-2.84	1.32	1.97	-1.4	-1.1
2.8	1.44	-2.84	1.74	1.94	-1.78	-1.44
4.6	1.66	-2.84	2.02	1.91	-2.12	-1.66
6.2	1.86	-2.84	2.29	1.89	-2.44	-1.86
8	1.25	-2.84	1.62	1.96	-1.75	-1.25

Mean and maximum values of standard deviation were 2.24 and 3.18 kPa, respectively. Mean and maximum values of DP estimation error were 1.85 and 48%, respectively. Mean and maximum values of DP total uncertainty were 1.31 and 1.84 kPa. Mean estimation error of t_{max} is 2% for 10500 kPa POP.

When the ROD parameter is constant, the only variable parameter is POP. Increase in POP intensifies collision between fluid molecules, which leads to increase in $\dot{m}_{REF}$. In fact, the discharged compressed nitrogen gas velocity through orifice increases by increase in POP. Therefore, the local pressure drop increases in orifice and pressure drop rate in Route 3 approach pressure drop rate in Route 2 (ROD). The difference between $\dot{m}_{PL}$ and $\dot{m}_{REF}$ decreases and consequently, the DP decreases.

Figure 8 represents the DPS in terms of ROD as a function of POP. It is necessary to know all parameters about the range of gas pipeline operating pressure and pressure drop rates to regulate the ALCV. The rate of pressure drop in normal operating conditions is lower than ROD at the same POP. It is necessary to select a ROD higher than pipeline pressure drop rate during normal operation and lower than all possible RODs to regulate the ALCV. The DPS results can be practically applied by adding 15% safety factor because of the use of nitrogen gas instead of natural gas and the uncertainties. To a real gas pipeline rupture in which the ROD valve and the pipeline operating pressure (POP) are different with the experimental values obtained in this work, new values can be found using interpolation in Fig.8 with drawing parabolic curves. The maximum and average percent of error for all conditions of DP estimation are 3.63 and 0.8%, respectively.

The DPS and ROD can be determined for specified POP by Fig.8. Each curve is denoted for specified POP. A value higher than the designed normal pipeline pressure drop rate can be selected for ROD. Finally, the DPS is determined by the indicated values of POP and ROD. For example, for 3 kPa/s designed normal pipeline pressure drop rate, ROD of 3.2 kPa/s can be selected. For POP=5000 kPa and ROD=3.2 kPa/s, the DPS is determined to be 130 kPa. Accordingly, the spring of NC valve can be loaded for 113.1 kPa by adding 13% safety factor.

Table 12. t_{max} for 10500 kPa POP

ROD	0.2	2.8	4.6	6.2	8
Estimated Value	90	96	92	90	89
Estimation Error %	0	6.7	2.2	0	1.1

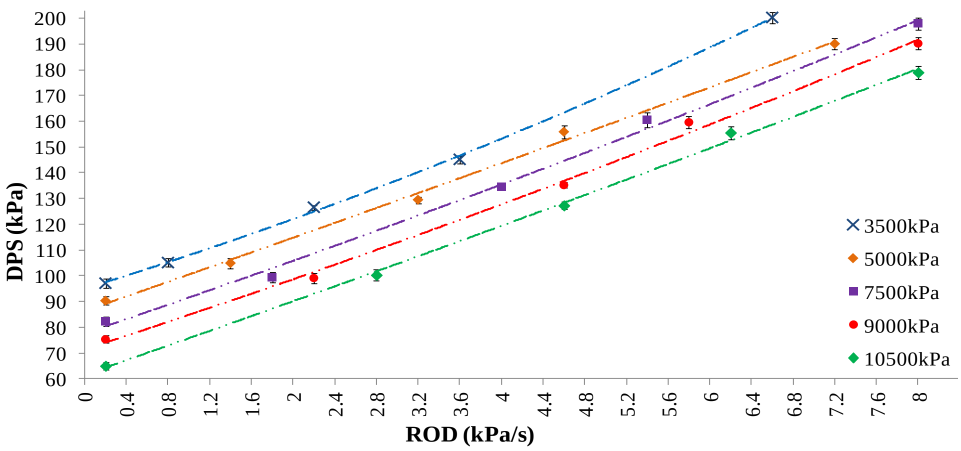

Fig. 8. DPS in terms of ROD for different POPs with gray continuous estimation curves.

Table 13. Data analysis of DPS estimation

POP	ROD	DPS	Estimated DPS	Error %	POP	ROD	DPS	Estimated DPS	Error %
3500	0.2	97.1	94.65	2.5	5000	0.2	90.3	88.61	1.87
	0.8	103.93	102.1	1.77		1.4	104.9	103.1	1.69
	2.2	126.6	125.36	0.98		3.2	129.5	128.54	0.73
	3.6	145.2	144.4	0.55		4.6	155.9	155.6	0.19
	6.6	200.33	197.47	1.43		7.2	190.1	187.46	1.37
7500	0.2	82.36	78.81	4.32	9000	0.2	75.26	72.52	3.64
	1.8	99.43	96.72	2.73		2.2	99.1	97.6	1.51
	4	134.6	132.87	1.28		4.6	135.2	133.58	1.19
	5.4	160.46	159.53	0.58		158	159.6	158.26	0.85
	8	198	195.58	1.07		8	190.2	187.19	1.58
10500	0.2	65	60.63	6.71	10500	6.2	155.56	154.52	0.67
	2.8	100.3	98	2.32		8	179	175.72	1.83
	4.6	127.26	125.16	1.65					

In Table 13, the data analysis of DPS estimation is presented for any condition. The DPS values in Fig.9 can be predicted by a proposed Eq.(7). In this equation, the ROD and POP are in kPa/s and kPa, respectively. The constant parameters of *h*, *k* and *i* in Eq.(7) are presented in Table 14.

$$\mathrm{DPS} = h(\mathrm{ROD})^2 + k(\mathrm{ROD}) + i(\mathrm{POP}) \qquad (7)$$

Table 14. Data analysis of Equation 7

POP	h	k	i	R^2
3500	0.52	12.46	0.027	0.999
5000	0.06	14.13	0.017	0.996
7500	0.018	13.69	0.011	0.996
9000	0.24	13.1	0.008	0.997
10500	0.1	14.04	0.006	0.998

The mentioned safety factor is based on limited available practical data. These data are related to practical conditions of ALCV installation in gas transportation pipelines of Iran. Data show that 15% safety factor is sufficient and reliable for using the results of this paper in practical applications. Comparison of natural gas and nitrogen is presented in Table 15. It should be mentioned that performing experiments using natural gas in laboratory is extremely dangerous. This safety factor is mainly related to the mass density. The mass density of natural gas and nitrogen at 0^o C temperature and 101.325 kPa pressure is 0.9 kg/m^3 and 1.2 kg/m^3, respectively.

Table 15. Comparison of DPS for natural gas and nitrogen

POP	ROD	DPS (Nitrogen)	DPS (Natural Gas)	Safety Factor
5000	1	188.5	166.7	11.6%
7500	1.4	197.2	170	13.8%

The non-dimensional DPS and ROD are named DOP and RTP, respectively. The DOP and RTP parameters are calculated by Equations 8 and 9, respectively.

$$\mathrm{DOP} = \mathrm{DPS}/\mathrm{POP} \qquad (8)$$

$$\mathrm{RTP} = \mathrm{ROD} \times t_{max}/\mathrm{POP} \qquad (9)$$

The DOP and RTP values are calculated by using experimental values and are shown in Table 17. The DOP in terms of RTP for different POPs is shown in Fig.9. The DOP can be defined by a linear equation (Eq.(10)) of RTP for each POP value.

$$\mathrm{DOP} = m(\mathrm{ROP}) + n \qquad (8)$$

The constant parameters of *m* and *n* in Eq.(10) are presented in Table 16. The R square coefficient for each predicted line is shown in Table 16. The proportion of the variance in the dependent variable (DOP) that is predictable from the independent parameter (RTP) is calculated by this coefficient.

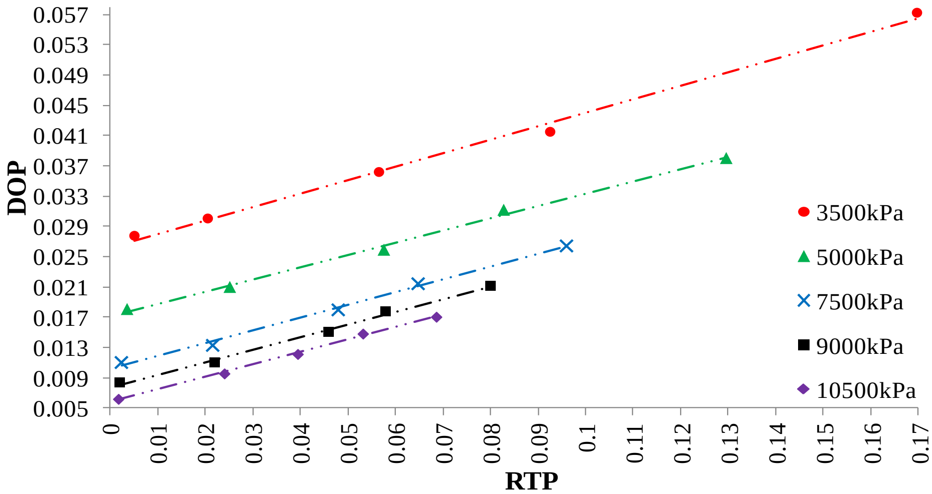

Fig. 9. DOP in terms of RTP for different POPs

Table 16. Data analysis of DOP estimation

POP	Error %		m	n	R^2
	Mean	Max.			
3500	1.67	2.88	0.18	0.026	0.995
5000	1.69	3.71	0.16	0.017	0.996
7500	2.4	3.41	0.17	0.01	0.995
9000	2.44	6.1	0.17	0.008	0.995
10500	1.59	3.65	0.16	0.006	0.998

The data analysis of DOP estimation and its error instead of actual value are presented for each condition in Table 17. The mean error for all conditions was 1.96% which shows a good accuracy for predicted values based on experimental values.

4. Conclusions

In this paper, the effect of parameters such as POP and ROD on the DPS of an automatic control valve was studied by performing 75 experimental tests. Statistical and uncertainty analysis were performed. The compressed nitrogen gas was used instead of natural gas because of the hazardous conditions present in pressurized natural gas. The following conclusions are justified:

- The DP values over a 180 s duration are affected by the POP and ROD. The DPS is increased by increasing ROD or decreasing POP.
- The DPS is first increased and then, decreased in all conditions. The DP with respect to time can be calculated using the proposed Eq.(1). The coefficients of this equation are presented for each condition. The averages of maximum and mean percent error for all conditions of DP estimation are 3.6 and 28.8%, respectively.
- Equation 6 was proposed for estimating t_{max}. The mean percent error of this estimation was 2.7% for all conditions. The t_{max} is predicted by the proposed equation with good accuracy for different conditions.
- The mean error in DPS estimation using Eq.(7) is 1.8% and the maximum error is 6.7% for 10500 kPa POP and 0.2 kPa/s ROD condition. The DPS is predicted by the proposed equation with very good accuracy for different conditions.
- The mean error in DOP estimation using Eq.(10) is 1.96% and the maximum error is 6.1% for 9000 kPa POP and 0.022 RTP condition. The DOP is predicted by the proposed equation with good accuracy for different conditions.
- The recommended DPS from this study can be practically applied by adding a safety factor of 15% to the experimental values.

Table 17. Data analysis of DOP estimation

POP	RTP	DOP	Estimated DOP	Error %	POP	RTP	DOP	Estimated DOP	Error %
3500	0.005	0.028	0.027	2.88	5000	0.004	0.018	0.018	0.06
	0.021	0.03	0.03	1.13		0.025	0.021	0.022	2.43
	0.057	0.036	0.036	0.19		0.058	0.026	0.027	3.72
	0.093	0.041	0.042	2.53		0.083	0.031	0.031	1.14
	0.17	0.057	0.056	1.63		0.13	0.038	0.038	1.11
7500	0.002	0.011	0.01	4.83	9000	0.002	0.008	0.008	0.08
	0.022	0.013	0.014	3.41		0.022	0.011	0.012	6.18
	0.048	0.018	0.018	1.37		0.046	0.015	0.016	4.59
	0.065	0.021	0.021	1.79		0.058	0.018	0.018	0.14
	0.096	0.026	0.026	0.67		0.08	0.021	0.021	1.21
10500	0.002	0.006	0.006	0.07	10500	0.053	0.015	0.015	0.55
	0.024	0.01	0.01	3.65		0.069	0.017	0.017	1.05
	0.039	0.012	0.012	2.66					

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