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Set Points Values of an Automatic Line Control Valve Installed on Natural Gas Pipeline

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ABSTRACT: When a natural gas pipeline ruptures, the adjacent automatic line control valves should close quickly to prevent leakage or explosion. The differential pressure set point at each valve position has an essential role for value determining in automatic line control valves action. This study focused on the differential pressure set point values prediction for setting automatic line control valves installed on a gas pipeline. The effect of characteristic parameters such as pipeline operational pressure and pipeline pressure drop rate due to major leak or abrupt rupture was experimentally examined on differential pressure set point. 25 different conditions with double set of typical indicated characteristic factors were selected. The differential pressure for any unique condition was measured in 180s time duration by analyzing the experimental outcomes, statistically. The differential pressure set point increases by changing such as increase in pipeline pressure drop rate or decrease in pipeline operational pressure parameters. Due to applying nitrogen gas instead of natural gas on account of safety claiming, the differential pressure set point results practically can be implemented by adding a 15% safety coefficient. The diagram of differential pressure set point with respect to defined parameters was presented for different values of pipeline operational pressure.

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1- Introduction

Natural gas is one of the important energy sources in the world and has an important role in industry and economy sections. Natural gas transportation and distribution are commonly performed in all nations through the gas pipelines network. Construction of new pipelines among countries will be increased [1]. Natural gas supplies almost one-fourth of all energy used in the world [2]. Leak detection systems are a major element in the design and development of Automatic Line Control Valves (ALCVs) installed on gas transportation pipelines and their contribution to the overall performance of ALCVs is hard to overestimate [3]. 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 the point of view of economic, environment and safety aspects. ALCVs are widely installed on oil and gas pipelines petroleum, chemical industry and nuclear power industries for these aspects [4,5]. When a natural gas 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 [6,7]. Several studies on leakage and ruptures detection in gas pipelines have been reported [8-17]. However, a few studies on setting the Differential Pressure Set point (DPS) values of ALCVs were performed which most of them are about different value setting between gas pipelines [18-24].

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The DPS value is the important parameter that determines whether an ALCV closes in time or not. Because of the changing operating conditions along a pipeline, Calculation of DPS values for ALCVs is complex. The DPS values have been usually adopted based on experiences. Because of high sensitivity on the pressure rate change over time in various pipeline conditions, the ALCV requires detailed and accurate setting. The normal pressure drop rate is due to frictional losses in a piping system. The normal pressure drop should not force the ALCV to operate. Actually, the Differential Pressure (DP) value between two sides (right and left) of diaphragm valve (Fig. 1) is DP. When DP value equals DPS, diaphragm moves to right and change Normally Closed (NC) valve position. The regulation of ALCV will be done with certain DPS for distinctive conditions. DP value is contingent upon particular parameters such as Pipeline Operating Pressure (POP) and rate of pressure drop due to rupture or large leak (ROD). The orifice diameter (Fig. 1) is another important parameter of ALCV. The orifice diameter is constant in this study. It equals 0.7 mm. As mentioned, the DPS values of ALCV are usually chosen based on practical or estimated data extracted from steady flow in pipeline over a long time.

In this study, the effects of important parameters such as POP and ROD on DPS of ALCV were experimentally studied. Recognizing the impacts of these parameters is prominent for designing and regulating ALCVs. 25 different classic conditions were chosen with double set of referred parameters. Each condition was studied 3 times in experimental method, so 75 tests were done. The DP over 180 s for each condition was portrayed by statistical analysis of the experimental results. Eventually, 25 DPSs with their occurrence times were obtained. Sequences of equations were built which relating the DP value over 180 s to the time for different values of

Uncertainty analysis was also executed and a series of equations relating the Non-dimensional Differential Pressure Set point (DOP) to the Non-dimensional Pipeline Pressure Drop Rate (RTP) for various POPs were presented.

2- Experimental Facilities and Setup

The schematic of experimental test setup is depicted in Fig. 1. The facilities used in this study are depicted in Fig. 2. The gaseous fluid pressure is transmitted from pipeline to ALCV through connecting hose and tubes. This is separated into three branched tube routes. The route 1 is 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) Pressure Transducer (PT) signals receiver, (7) 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). For avoiding any hazardous conditions or catastrophic explosion, nitrogen gas was used instead of natural gas. The pressure of pipeline is reached to the desired value of POP by using a compressed nitrogen cylinder (No.2 in Fig. 2) via connecting hose as shown in Fig. 2.

The cylinder valve is closed when all routes in Fig. 1 have the identical pressure as POP. Pressure gauges in Fig. 2 are

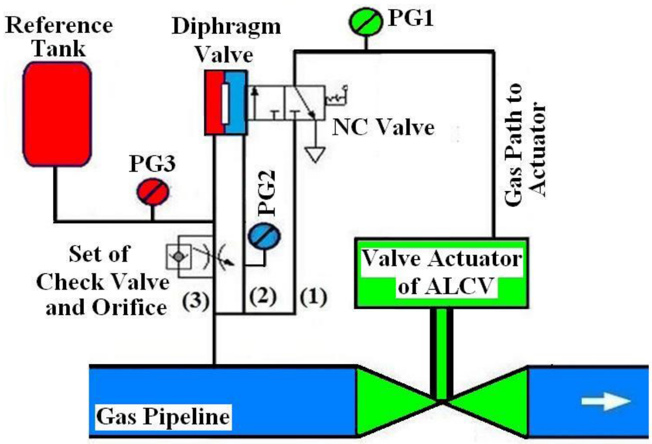

Fig. 1. Experimental setup scheme

not considered for data recoding. A calibrated valve (No.11 in Fig. 2) is fasten to the pipeline to produce a ROD value for 180 s time duration by extracting compressed nitrogen gas to surrounding space. Nitrogen gas goes to the reference tank by a device which is consisted of orifice and check valve (No.8 in Fig. 2) located in Route 3 (Fig. 1). Based on the lower pressure drop, it is clear that the fluid chooses the route with check valve instead of orifice. In any time, the reference tank

Fig. 2. Experimental test setup scheme

pressure is identical to the pipeline pressure. When a rupture or failure happens spontaneously in transmission pipeline, the reference tank pressure will be greater than pipeline pressure. In this time, the route which contains check valve is blocked. Hence, all the fluid in reference tank transports inside the orifice. This produces new pressure drop rate in the system which is lower than the ROD value. The differential pressure between pipeline and reference tank is identical to the DP between two sides of the diaphragm valve. The ALCV acts when DP attains to maximum value (DPS) and the normally closed valve position changes at the end.

The pressure of isolated pipeline is reached to a constant value and then the pressure is reduced for 5 minutes by opening the valve (No.11 in Fig. 2) which is located on pipeline. The mean ROD (kPa/s) value should be evaluated for this specific valve opening (in degree). The pressure difference (kPa) between the initial time and 5 minutes after valve opening was divided to 300 seconds (test time duration) to compute the ROD. After that the ROD has been gained for this specific valve opening. This process was repeated 3 times for this settled valve opening to obtain the mean ROD. As a result, the valve calibration was carried out by 45 tests (15 ROD× 3 times repetition) for whole conditions. Eventually, the valve was calibrated for 9 ROD values from 0.2kPa/s up to 4.2kPa/s. The pressure transducers (No.7 in Fig. 2) were calibrated by a Yantrika hydraulic dead weight tester. Cables and amplifier uncertainties are negligible. 25 different typical conditions were summarized in Table 1 based on 5 different values for the POP and 15 different values for the ROD. Each condition was experimentally studied 3 times, so 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.

Table 1. Experimental parameters and their values

Parameter	Unit	Values
POP	kPa	3500, 5000, 7500, 9000, 10500
ROD	kPa/s	0.2, 0.4, 0.8, 1, 1.4, 1.8, 2, 2.2, 2.4, 2.6, 2.8, 3, 3.6, 3.8, 4.2

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

3- Discussion on Results

As indicated before, DPS can be settled in accord with the maximum DP values over 180 s. 25 various conditions were executed based on the parameters shown in Table 1. Rupture was happened at beginning time (t=0) by ROD. The DP enlarged versus time to DPS as a maximum value and then it declined for whole conditions. The DP versus time has shown based on received data from two pressure transducers (PG2 and PG3) for 180 s after pipeline-failure for any 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.

Actually, this is the result of essential behavior of the orifice and check valve collection (No.8 in Fig. 2) in ALCV. The DP is determined as a function of ROD and POP parameters. The DP values are estimated by Eq. (1) over 180 s for whole conditions. Any condition has its six unique constant coefficients such as a, b, c, d, e and f. These six constant coefficients are presented in Tables 3, 5, 7, 9 and 11 for any condition. In fact, these coefficients are unfamiliar functions of ROD and POP.

$$\mathrm{DP} = a\,e^{bt} + c\,Ln\left(1+dt\right) + e\,t + f \tag{1}$$

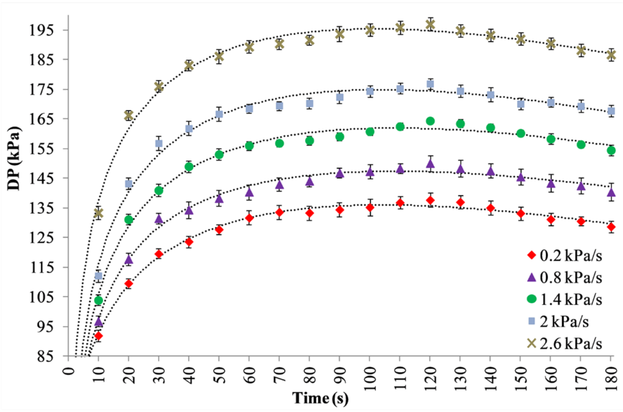

Fig. 3. DP versus time for 3500 kPa POP

Each row in these tables is the result for any unique 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 Eq. (2). Standard Deviation (SD) relies on least squares fitting and it is calculated by Eq. (3). Maximum and mean values of SD are described. Error bars are presented dependent on SD in Figs. 3 to 7. For parameter x, uncertainty of experimental test repetition and uncertainty of its measuring equipment are depicted by U_{rep} and U_{tool}, respectively. The half measuring equipment accuracy is h_a in Eq. (4). Total uncertainty of any experimental test (U_{tot}) is explained by Eq. (4). Average and maximum values of total uncertainty in DP measurements for any condition are presented.

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

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

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

Table 2. Equipment and their uncertainties

Equipment and Model	Accuracy	Measured Section	Test Range	Uncertainty in Experiment
LCD Digital Stopwatch (Sigma-Aldrich, Germany)	± 0.003%	t, ROD	0-180 s	± 5.4×10^{-3} s
Pressure Transducer, PXM01MD0-160BARG5T (Omega, UK)	± 0.05%	POP, DP, DPS, ROD	2060-10500 kPa	± 0.22% (± 8 kPa)

Table 3. Coefficients in Equation 1 for 3500 kPa POP

ROD	*a*	*b*	*c*	*d*	*e*	*f*
0.2	-5.15×10	-2.84×10^{6}	3.8×10	2.21×10^{-1}	-3.5×10^{-1}	5.15×10
0.8	2.1×102	-2.84×10^{6}	3.4×10	9.25×10^{2}	-3.14×10^{-1}	-2.1×10^{2}
1.4	2.69×102	-2.84×10^{6}	3.82×10	2×10^{3}	-3.52×10^{-1}	-2.69×10^{2}
2	2.89×102	-2.84×10^{6}	4.12×10	2.01×10^{3}	-3.97×10^{-1}	-2.89×10^{2}
2.6	2.68×102	-2.84×10^{6}	4.13×10	2.01×10^{3}	-4.07×10^{-1}	-2.68×10^{2}

Mean and maximum values of standard deviation were 1.89 and 2.91 kPa, respectively. Mean and maximum values of DP estimation error were 0.81% and 4.04%, respectively. Mean and maximum values of DP total uncertainty were 1.1 and 1.68 kPa. Mean estimation error of tmax is 14.64% for 3500 kPa POP.

Table 4. t_{max} for 3500 kPa POP

ROD	0.2	0.8	1.4	2	2.6
Estimated Value	104	108	102	100	98
Estimation Error	13.3%	10%	15%	16.6%	18.3%

The percent error of DP prediction is calculated by using Eq. (5). For any condition, estimated value of DP is in perfectly coincidence with its gained experimental data.

$$\text{Estimation error }\% = \frac{\left|\text{Estimated value} - \text{Experimental value}\right|}{\text{Experimental value}}\times 100 \tag{5}$$

According to the experimental tests, the required time to attain maximum DP (t_{max}) is 120 seconds. The estimated value of t_{max} is calculated by solving Eq. (6) which is derivation of Eq. (5). The estimated values of t_{max} and their errors are exhibited in Tables 4, 6, 8, 10 and 12 for any condition.

$$abe^{bt} + \left(c\times d\right)/\left(1+dt\right) + e = 0 \tag{6}$$

The only variable parameter is ROD when the POP is constant. The increase of ROD causes an increase in DP for other constant parameter (POP) for whole conditions. More mass of compressed nitrogen gas in pipeline ($\dot{m}_{PL}$) is discharged to surrounding space by enlarging the ROD. The pressure of ALCV equals the pipeline pressure at the beginning time before pipeline failure. The pressure drop rate on the right side of the diaphragm valve (Fig. 1) is identical to 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 transporting inside the orifice.
Mean and maximum values of standard deviation were 2 and 2.75 kPa, respectively. Mean and maximum values of DP estimation error were 0.83% and 2.85%, respectively. Mean and maximum values of DP total uncertainty were 1.17 and 1.72kPa. Mean estimation error of t_{max} is 12.2% for 5000 kPa

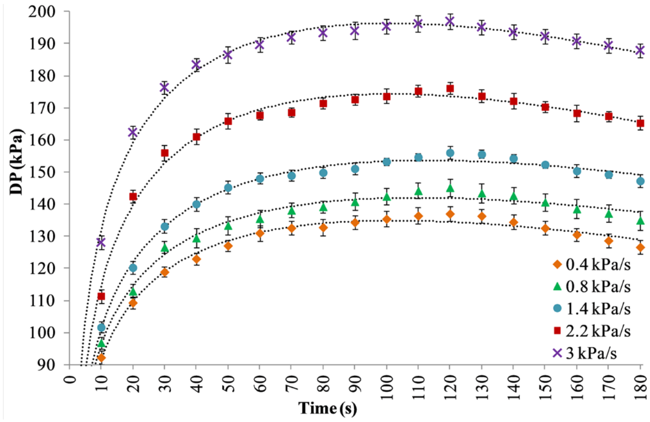

Fig. 4. DP versus time for 5000 kPa POP

Table 6. t_{max} for 5000 kPa POP

ROD	0.4	0.8	1.4	2.2	3
Estimated Value	102	109	113	101	102
Estimation Error	15%	9.2%	5.8%	15.8%	15%

POP.
Always, the $\dot{m}_{PL}$ is identical or bigger than the discharged mass flow rate of the reference tank ($\dot{m}_{REF}$). The $\dot{m}_{PL}$ value increases by increase in ROD. Eventually, the distinction between $\dot{m}_{PL}$ and $\dot{m}_{REF}$ is increased which resulting increases the DP. This DP increases to a maximum value and then decreases because of the mass diminishing of compressed nitrogen gas through the reference tank. Therefore, the pressure of reference tank appeal to the pressure of pipeline.
Mean and maximum values of standard deviation were 1.98 and 2.8 kPa, respectively. Mean and maximum values of DP estimation error were 0.8% and 3.63%, respectively. Mean and maximum values of DP total uncertainty were 1.16 and 1.62 kPa. Mean estimation error of t_{max} is 10.94% for 7500 kPa POP.
Mean and maximum values of standard deviation were 1.99 and 2.85 kPa, respectively. Mean and maximum values of DP estimation error were 0.8% and 2.96%, respectively. Mean and maximum values of DP total uncertainty were 1.16 and 1.64 kPa. Mean estimation error of t_{max} is 12.48% for 9000 kPa POP.

Table 5. Coefficients in Equation 1 for 5000 kPa POP

ROD	*a*	*b*	*c*	*d*	*e*	*f*
0.4	2.1×10^{2}	-2.84×10^{6}	3.07×10	2.01×10^{3}	-3×10^{-1}	-2.1×10^{2}
0.8	2.09×10^{2}	-2.84×10^{6}	3.11×10	2.01×10^{3}	-2.84×10^{-1}	-2.09×10^{2}
1.4	2.43×10^{2}	-2.84×10^{6}	3.5×10	2.01×10^{3}	-3.1×10^{-1}	-2.43×10^{2}
2.2	3.03×10^{2}	-2.84×10^{6}	4.26×10	2.01×10^{3}	-4.22×10^{-1}	-3.03×10^{2}
3	3.16×10^{2}	-2.84×10^{6}	4.56×10	2.01×10^{3}	-4.5×10^{-1}	-3.16×10^{2}

Table 7. Coefficients in Equation 1 for 7500 kPa POP

ROD	*a*	*b*	*c*	*d*	*e*	*f*
0.2	2.17×10^2	-2.84×10^6	3.07×10	2.01×10^3	-2.99×10^{-1}	-2.17×10^2
0.8	2.16×10^2	-2.84×10^6	3.12×10	2.01×10^3	-2.78×10^{-1}	-2.16×10^2
1.8	2.65×10^2	-2.84×10^6	3.72×10	2.01×10^3	-3.25×10^{-1}	-2.65×10^2
2.8	3.57×10^2	-2.84×10^6	4.83×10	2×10^3	-4.84×10^{-1}	-3.57×10^2
3.6	3.24×10^2	-2.84×10^6	4.67×10	2.01×10^3	-4.56×10^{-1}	-3.24×10^2

Table 8. t_{max} for 7500 kPa POP

ROD	0.2	0.8	1.8	2.8	3.6
Estimated Value	103	113	115	100	103
Estimation Error	14.1%	5.8%	4.1%	16.6%	14.1%

Table 9. Coefficients in Equation 1 for 9000 kPa POP

ROD	*a*	*b*	*c*	*d*	*e*	*f*
0.2	2.17×10^2	-2.84×10^6	3.01×10	2.01×10^3	-2.87×10^{-1}	-2.17×10^2
1.4	2.78×10^2	-2.84×10^6	3.72×10	2.01×10^3	-3.45×10^{-1}	-2.78×10^2
2.4	3.19×10^2	-2.84×10^6	4.3×10	2×10^3	-3.98×10^{-1}	-3.19×10^2
3	3.03×10^2	-2.84×10^6	4.28×10	2.01×10^3	-4.28×10^{-1}	-3.03×10^2
3.8	3.14×10^2	-2.84×10^6	4.53×10	2.01×10^3	-4.44×10^{-1}	-3.14×10^2

Table 10. t_{max} for 9000 kPa POP

ROD	0.2	1.4	2.4	3	3.8
Estimated Value	105	108	109	101	102
Estimation Error	12.5%	10%	9.1%	15.8%	15%

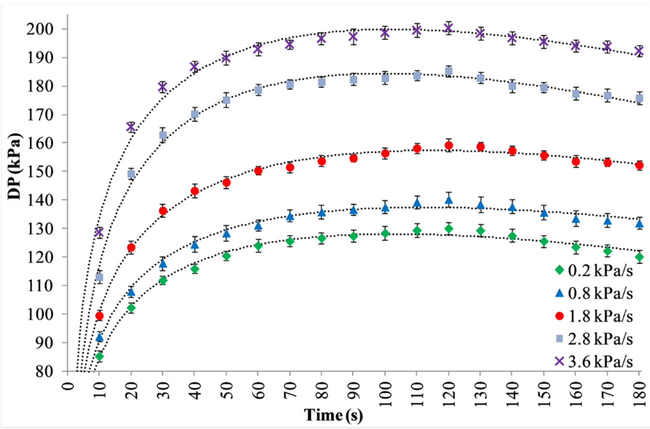

Fig. 5. DP versus time for 7500 kPa POP

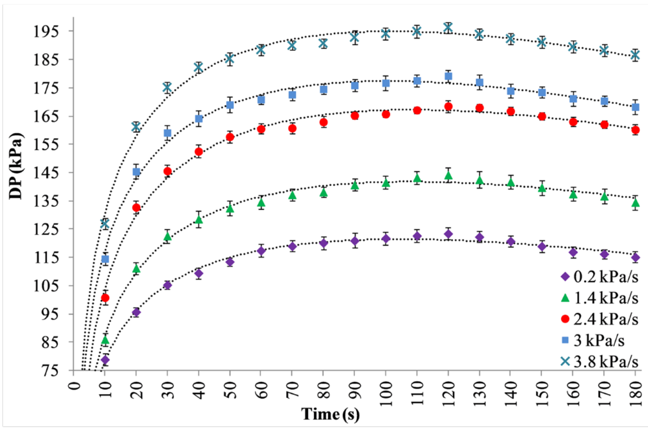

Fig. 6. DP versus time for 9000 kPa POP

Mean and maximum values of standard deviation were 1.97 and 2.86 kPa, respectively. Mean and maximum values of DP estimation error were 0.78% and 3.12%, respectively. Mean and maximum values of DP total uncertainty were 1.16 and 1.65 kPa. Mean estimation error of t_{max} is 11.16% for 10500 kPa POP.

The only inconstant parameter is POP when the ROD parameter is constant. Increase in POP strengthens fluid molecules collision which results to increase in $\dot{m}_{REF}$. By increase in POP, the discharged compressed nitrogen gas velocity inside orifice increases. Consequently, the local pressure drop increases in orifice and pressure drop rate in Route 3 closes to pressure drop rate in Route 2. The difference between values of $\dot{m}_{PL}$ and $\dot{m}_{REF}$ reduces and finally, the DP declines.

Fig. 8 depicts the DPS in terms of ROD as a function of POP. It is prominent to know all parameters in the range of gas pipeline operating pressure and pressure drop rates to manage the ALCV. The pressure drop rate in normal operating conditions is lower than ROD at the identical POP. It is essential to choose a ROD higher than pipeline pressure drop rate during normal performance and lower than whole possible RODs to adjust the ALCV. The DPS values can be used for industrial aims by adding 15% safety factor due to applying nitrogen gas in place of natural gas and the uncertainties. In a real gas pipeline failure which the ROD

Table 11. Coefficients in Equation 1 for 10500 kPa POP

ROD	*a*	*b*	*c*	*d*	*e*	*f*
0.2	2.31×10^{2}	-2.84×10^{6}	3.06×10	2.01×10^{3}	-2.95×10^{-1}	-2.31×10^{2}
1	2.53×10^{2}	-2.84×10^{6}	3.38×10	2.01×10^{3}	-3.03×10^{-1}	-2.53×10^{2}
2	3.04×10^{2}	-2.84×10^{6}	3.99×10	2×10^{3}	-3.6×10^{-1}	-3.04×10^{2}
2.6	3.35×10^{2}	-2.84×10^{6}	4.41×10	2.01×10^{3}	-4.3×10^{-1}	-3.35×10^{2}
4.2	3.53×10^{2}	-2.84×10^{6}	4.91×10	2.01×10^{3}	-4.83×10^{-1}	-3.53×10^{2}

Table 12. t_{max} for 10500 kPa POP

ROD	0.2	1	2	2.6	4.2
Estimated Value	104	112	112	103	102
Estimation Error	13.3%	6.7%	6.7%	14.1%	15%

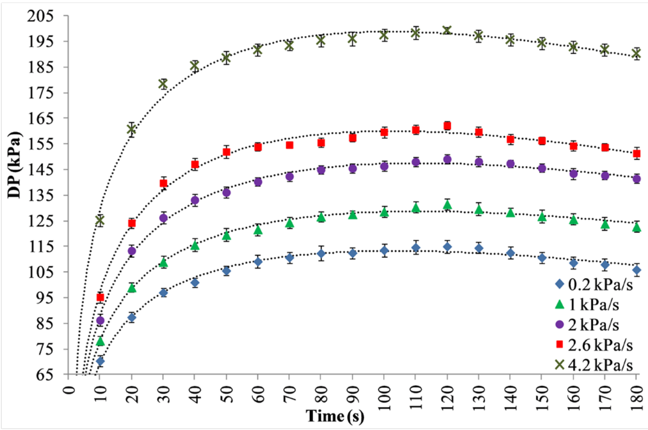

Fig. 7. DP versus time for 10500 kPa POP

and POP values are at variance with the experimental values gained in this study, new values can be obtained by 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.

For example, the DPS and ROD can be determined for specified POP. Each curve is denoted for specified POP. A

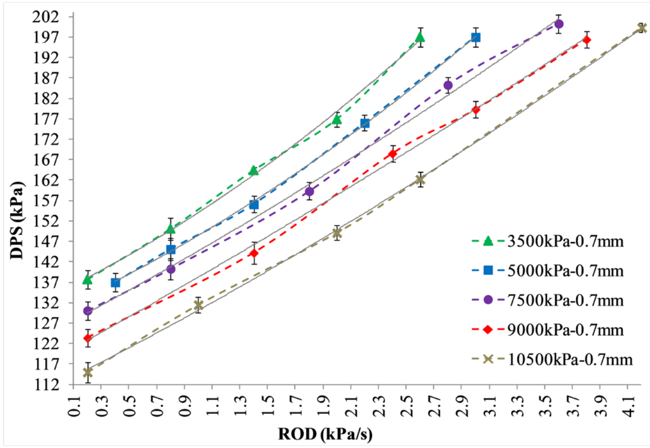

Fig. 8. DPS in terms of ROD for different POPs with gray continuous estimation curves.

value bigger 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 1.3 kPa/s designed normal pipeline pressure drop rate, ROD can be selected 1.5 kPa/s. For POP=5000 kPa and ROD=1.5 kPa/s, the DPS is determined to be 153 kPa. Accordingly, the spring of NC valve can be loaded for 130.1 kPa by adding 15% safety factor.

The data analysis of DPS estimation is presented for any condition in Table 13. The DPS values in Fig. 9 can be predicted by a proposed Eq. (7). In this equation, the ROD

Table 13. Data analysis of DPS estimation

POP	ROD	DPS	Estimated DPS	Error	POP	ROD	DPS	Estimated DPS	Error
3500	0.2	137.7	135.6	1.52%	5000	0.4	137.1	134.4	1.64%
	0.8	150.1	147.2	1.95%		0.8	145.2	141.9	2.3%
	1.4	164.4	161.7	1.65%		1.4	156.1	153.5	1.62%
	2	175.3	174.4	1.43%		2.2	175.9	173.6	1.46%
	2.6	197	194.7	1.15%		3	197	195.6	0.7%
7500	0.2	130.1	127.7	1.86%	9000	0.2	123.4	121.2	1.87%
	0.8	140.3	137.3	2.09%		1.4	144.2	141.6	1.83%
	1.8	159.4	157.2	1.35%		2.4	168.5	167	0.89%
	2.8	185.3	183.47	1.15%		3	179.3	176.6	1.17%
	3.6	200.3	199.2	0.55%		3.8	196.4	194.3	1.05%
10500	0.2	115	112.9	1.85%					
	1	131.5	128.6	2.24%					
	2	149.1	147.3	1.21%					
	2.6	162.2	159.4	1.73%					
	4.2	199.3	198	0.66%					

and POP are in kPa/s and kPa, respectively. The constant parameters of h and k in Eq. (7) are presented in Table 14.

$$DPS = h(ROD)^2 + k(ROD) - 0.0031(POP) + 146.3 \tag{7}$$

Table 14. Data analysis of Eq. (7)

POP	*h*	*k*	R^2
3500	2.7	16.68	0.997
5000	2.15	15.73	1
7500	0.85	17.92	0.997
9000	0.46	18.71	0.998
10500	0.87	17.06	0.999

The presented safety factor is based on restricted available experimental value. These values are related to industrial real conditions of ALCV installation in Iran gas transportation pipelines. Experimental values depict that 15% safety factor is reliable and adequate for using this paper results in industrial implementation. Comparison of nitrogen and natural gas are shown in Table 15. It should be hinted that executing experimental tests which using natural gas in laboratory is exceedingly perilous. This safety factor is mostly related to the mass density. The mass density of nitrogen and natural gas at Standard Temperature and Pressure[1] (STP) are 1.2 kg/m^3 and 0.9 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 Eqs. (8) and (9), respectively.

$$DOP = DPS/POP \tag{8}$$

$$RTP = ROD \times t_{max}/POP \tag{9}$$

The DOP and RTP values are calculated by experimental results in Table 13. 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.

$$DOP = a(ROP) + b \tag{10}$$

The constant parameters of *a* and *b* in Eq. (10) are presented in Table 16.

Table 16. Data analysis of DOP estimation

POP	Mean DOP	Error		*a*	*b*	R^2
		Avg.	Max.			
3500	0.053	0.33%	1.07%	0.2	0.038	0.983
5000	0.04	0.62%	2.53%	0.19	0.025	0.97
7500	0.024	0.6%	1.92%	0.18	0.017	0.98
9000	0.019	0.73%	2.4%	0.17	0.013	0.99
10500	0.017	0.69%	1.63%	0.17	0.11	0.99

4- Conclusions

In this study, the impact of parameters such as POP and ROD on the DPS of an automatic control valve was investigated by executing 75 experimental tests. Uncertainty and statistical analysis were done. The compressed nitrogen gas was applied instead of natural gas because of the perilous situations in presence of highly pressurized natural gas. The below results and conclusions are extracted:

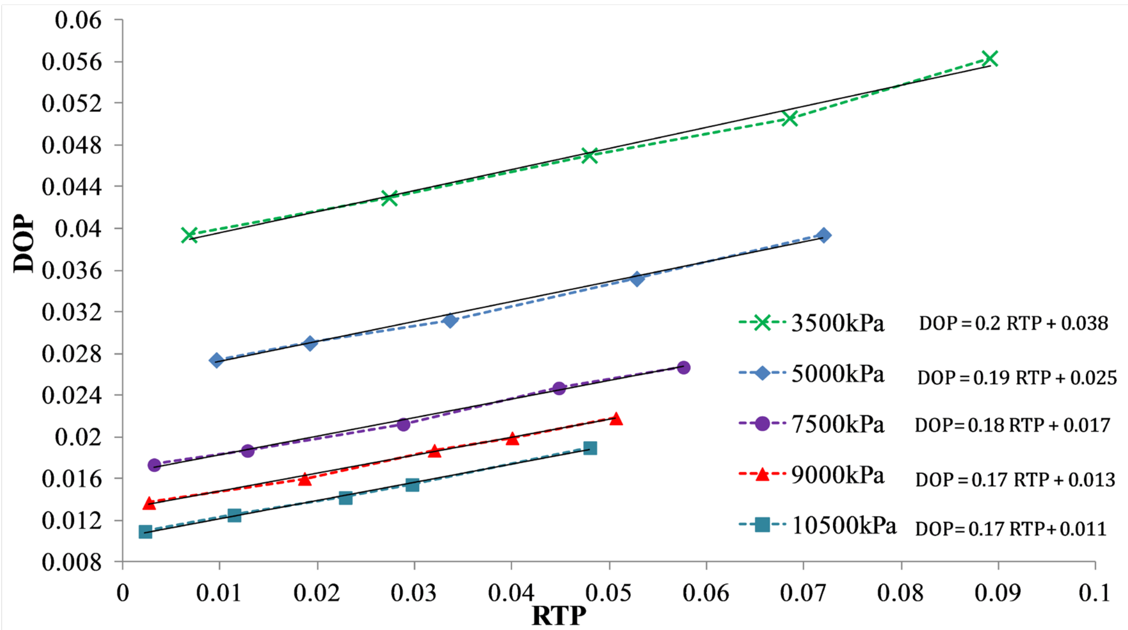

Fig. 9. DOP in terms of RTP for different POPs

1 0°C and 101.325 kPa

- The DP values over a 180 s duration time are influenced by the POP and the ROD. The DPS is enlarged by increasing ROD or declining POP.
- The DP with respect to time can be calculated using proposed Eq. (1). The coefficients of this equation are presented in Tables 3, 5, 7, 9 and 11 for any condition. The mean of average and maximum percent error for whole conditions of DP prediction are 0.8% and 3.63%, respectively.
- The Eq. (6) was proposed for estimating t_{max}. The mean percent error of this estimation was 12.28% for whole 25 conditions.
- The mean error in DPS estimation using Eq. (5) is 1.48% and the maximum error is 2.3% for 5000 kPa POP and 0.8 kPa/s ROD condition.
- The proposed DPS from this study can be practically used by applying a safety factor of 15% to the practical data which are extracted from experimental values in Fig. 8.

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