

An assessment of the thermal impact on the valve torque on cryogenically sub-zero temperatures

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INTRODUCTION

So-called Permanent gases (also called as cryogenics) such as Helium, Hydrogen, Argon, Nitrogen, Oxygen etc. are being liquefied in order to facilitate their transportation and storage due to less space and volume occupied post liquefaction. However, the challenge faced by industrialists and researchers constitutes the drawing off the gases from the cryogenic transport or storage tank with the required pressure and flow parameters. Therefore, the drawing off line of the cryogenic tanks are mounted with valves such as the ball, globe, check, safety valves etc. While the design seems very convenient for the hand-wheel operated isolation type globe and ball valves, the designer faces many difficulties in predicting, evaluating and concluding the most optimum design of the valve hand-wheel due to the enhanced torque required for the valve to operate at sub-zero temperatures. Currently, the designer is completely dependent on actual torque test on test bench post prototype development.

The research effort directs to analyze and study the behavioral pattern of torque of a cryogenic globe valve under different cryogenic conditions. It would be conducted on designed experiments methodology after monitoring the torque as response with pressure and temperature as varying factors at different levels.

The methodology also involves comparing the experiments analytically for evaluating torque for cryogenic globe valves.

The results will help the valve designer taking informed decision over predicting the torque the valve may generate (which is currently very difficult and completely dependent on actual torque test on test bench post prototype development).

DESIGN OF EXPERIMENTS

Methodology

A designed experiment, Montgomery [1], is a test or series of tests in which purposeful changes are made to the input variables of a process so that we may observe and identify corresponding changes in the output response. The process can be visualized as some combination of machines, methods, and people that transforms an input material into an output product. This output product has one or more observable quality characteristics or responses. Some of the process variables x_1, x_2, \dots, x_p are controllable, whereas others z_1, z_2, \dots, z_q are uncontrollable (although they may be controllable for purposes of the test). For the design of the cryogenic globe valve, operating pressure and temperature are considered to be the controllable factors in the designed experiments.

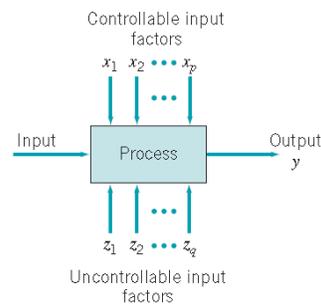


Figure 1. Design of experiments

Uncontrollable factors considered includes coefficient of friction depending on material, surface finish and the manufacturing process and the valve port area which is constant for any two same size globe valves. The experiment to be designed shall be full factorial design with 2 factors, each on 5 levels with 2 replicas of observation during experiments. Since the number of factors are pragmatic, the model would be fixed effects model. The observations from a two-factor factorial experiment may be described by the model:

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \quad \begin{cases} i = 1, 2, \dots, a \\ j = 1, 2, \dots, b \\ k = 1, 2, \dots, n \end{cases}$$

where μ is the overall mean effect, τ_i is the effect of the i th level of factor A, β_j is the effect of the j th level of factor B, $(\tau\beta)_{ij}$ is the effect of the interaction between A and B, and ε_{ijk} is random error component. Both factors are assumed to be fixed, and the treatments effects are defined as deviations from the overall mean so, $\sum_{i=1}^a \tau_i = 0$ and $\sum_{j=1}^b \beta_j = 0$. Similarly, the interaction effects are fixed and are defined such that, $\sum_{i=1}^a (\tau\beta)_{ij} = 0$ and $\sum_{j=1}^b (\tau\beta)_{ij} = 0$. Because there are n replicates of the experiments, there are abn total observations. Here, $a = 5$ $b = 5$ $n = 2$, thus total 50 observations.

Table 1 Arrangement for a two-factor full factorial design

$T_{Pai,Tai}$	$T_{Pai,Tbi}$	$T_{Pai,Tci}$	$T_{Pai,Tdi}$	$T_{Pai,Tei}$
$T_{Pbi,Tai}$	$T_{Pbi,Tbi}$	$T_{Pbi,Tci}$	$T_{Pbi,Tdi}$	$T_{Pbi,Tei}$
$T_{Pci,Tai}$	$T_{Pci,Tbi}$	$T_{Pci,Tci}$	$T_{Pci,Tdi}$	$T_{Pci,Tei}$
$T_{Pdi,Tai}$	$T_{Pdi,Tbi}$	$T_{Pdi,Tci}$	$T_{Pdi,Tdi}$	$T_{Pdi,Tei}$
$T_{Pei,Tai}$	$T_{Pei,Tbi}$	$T_{Pei,Tci}$	$T_{Pei,Tdi}$	$T_{Pei,Tei}$

$T_{P, T}$ = Torque observed at pressure P and temperature T
 $P_{low} = P_a = 1.3$ MPa, $P_b = 1.6$ MPa, $P_c = 2.15$ MPa, $P_d = 2.45$ MPa, $P_{high} = P_e = 2.94$ MPa
 $i = 1, 2$ for replicates of individual observations

Statistical analysis

Generally, let Y_i denote the total of all observations under i th level of factor A, Y_j denote the total of all observations under the j th level of factor B, Y_{ij} denote the total of all observations in the ij th cell, and Y denote the grand total of all observations. Define \bar{Y}_i , \bar{Y}_j , \bar{Y}_{ij} , \bar{Y} as the corresponding row, column, cell and grand averages. Expressed mathematically,

$$Y_i = \sum_{j=1}^b \sum_{k=1}^n Y_{ijk}, \quad \bar{Y}_i = Y_i \frac{1}{bn} \quad \text{for } i = 1, 2, \dots, a$$

$$Y_j = \sum_{i=1}^a \sum_{k=1}^n Y_{ijk}, \quad \bar{Y}_j = Y_j \frac{1}{an} \quad \text{for } j = 1, 2, \dots, b$$

$$Y_{ij} = \sum_{k=1}^n Y_{ijk}, \quad \bar{Y}_{ij} = Y_{ij} \frac{1}{n} \quad \text{for } i = 1, 2, \dots, a \text{ \& } j = 1, 2, \dots, b$$

$$Y = \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^n Y_{ijk}, \quad \bar{Y} = Y \frac{1}{abn}$$

The total corrected sum of squares may be written as

$$\begin{aligned} \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^n (Y_{ijk} - \bar{Y})^2 &= \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^n [(\bar{Y}_i - \bar{Y}) + (\bar{Y}_j - \bar{Y}) + (\bar{Y}_{ij} - \bar{Y}_i - \bar{Y}_j + \bar{Y}) \\ &\quad + (Y_{ijk} - \bar{Y}_{ij})]^2 \\ &= bn \sum_{i=1}^a (\bar{Y}_i - \bar{Y})^2 + an \sum_{j=1}^b (\bar{Y}_j - \bar{Y})^2 + n \sum_{i=1}^a \sum_{j=1}^b (\bar{Y}_{ij} - \bar{Y}_i - \\ &\quad \bar{Y}_j + \bar{Y})^2 + \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^n (Y_{ijk} - \bar{Y}_{ij})^2 \end{aligned}$$

This equation symbolically may be written as following

$$SS_T = SS_A + SS_B + SS_{AB} + SS_E \quad (1)$$

Table 2 Degrees of freedom associated with each sum squares

Effect	Degrees of Freedom
A	$a-1$
B	$b-1$
AB Interaction	$(a-1)(b-1)$
Error	$ab(n-1)$
Total	$abn-1$

Each sum of squares divided by its degrees of freedom is a mean square. The expected values of the mean squares are

$$E(MS_A) = E\left(\frac{SS_A}{a-1}\right) = \sigma^2 + \frac{bn \sum_{i=1}^a \tau_i^2}{a-1} \quad (2)$$

$$E(MS_B) = E\left(\frac{SS_B}{b-1}\right) = \sigma^2 + \frac{an \sum_{j=1}^b \beta_j^2}{b-1} \quad (3)$$

$$E(MS_{AB}) = E\left(\frac{SS_{AB}}{(a-1)(b-1)}\right) = \sigma^2 + \frac{n \sum_{i=1}^a \sum_{j=1}^b (\tau\beta)^2_{ij}}{(a-1)(b-1)} \quad (4)$$

$$E(MS_E) = E\left(\frac{SS_E}{ab(n-1)}\right) = \sigma^2 \quad (5)$$

Table 3 Analysis of variance

Source of Variation	Sum of Squares	Degrees of freedom	Mean Square	F ₀
A treatments	SS_A	$a-1$	$MS_A = \frac{(SS_A)}{a-1}$	$\frac{MS_A}{MS_E}$
B treatments	SS_B	$b-1$	$MS_B = \frac{(SS_B)}{b-1}$	$\frac{MS_B}{MS_E}$
Interaction	SS_{AB}	$(a-1)(b-1)$	$MS_{AB} = \frac{(SS_{AB})}{(a-1)(b-1)}$	$\frac{MS_{AB}}{MS_E}$
Error	SS_E	$ab(n-1)$	$MS_E = \frac{(SS_E)}{ab(n-1)}$	
Total	SS_T	$abn-1$		

Experiments

The experiment involves using two cryogenic tanks: one stationary and one mobile. The liquid nitrogen transported from either of the tank to the another at -196 °C (77 K) are at pressures 1.3,1.6,2.15 ,2.45 & 2.94 MPa respectively. For observations pertaining to varying temperatures below -196 °C (77 K), gas line of the cryogenic was also used.

Following are the key equipments used for the experiments:

- Cryogenic Valve Globe Valve DN15 PN50, Mack Valves make
- Temperature sensor, RTD PT100
- Pressure gauge
- Cryogenic tank, 200L, Chart make
- Pressure regulator valve
- Pressure safety valve
- Torque wrench (for Specification from 3 Nm to 20 Nm)
- Adaptor to mate the torque wrench with the valve Spindle
- Recommended Personal Protective Equipments (PPEs)

The experiments were conducted in premises of Industrial gas supplier M/S Abhijit Enterprises, Pune on media Liquid Nitrogen (LIN). The level of the factors is 5, pressure factor has low value of 14 Kg/cm² (1.3 MPa) and pressure factor has high value of 30 Kg/cm² (2.94 MPa). Similarly, temperature factor has low value of 90 K (-183 °C) and temperature factor has high value of 121 K (-152 °C). The data points were collected within 3 days.

After conducting the experiments, the data points are analyzed using statistical methods and analysis of variance is done. The tool used is Minitab 19 [3]. Uncertainty analysis and confidence interval is done at interval of 95% confidence.



Figure 2. Experimental set up

Table 4 Readings

P , kg/cm ²	T1, °C	T2, °C	ΔT, °C	Opening Torque, Nm
14	-152	-127	25	1.7
14	-150	-130	20	1.73
14	-172	-138	34	1.92
14	-170	-135	35	1.9
14	-163	-146	17	1.77
14	-162	-149	13	1.8
14	-182	-152	30	1.96
14	-185	-146	39	1.98
14	-183	-138	45	2.01
14	-185	-140	45	1.98
17	-162	-127	35	2.65
17	-159	-134	25	2.58
17	-150	-128	22	2.55
17	-152	-125	27	2.58
17	-185	-139	46	3.01
17	-185	-141	44	2.97
17	-178	-145	33	2.71
17	-175	-136	39	2.68
17	-167	-127	40	2.67
17	-168	-135	33	2.7
22	-172	-149	23	2.87
22	-174	-148	26	2.85

22	-153	-132	21	2.81
22	-152	-131	21	2.82
22	-163	-130	33	2.88
22	-160	-129	31	2.87
22	-178	-140	38	2.93
22	-179	-140	39	2.94
22	-178	-132	46	2.91
22	-180	-135	45	2.95
25	-163	-138	25	3.09
25	-165	-140	25	3.1
25	-153	-132	21	3.05
25	-150	-116	34	3.07
25	-163	-127	36	3.11
25	-164	-125	39	3.11
25	-166	-144	22	3.07
25	-168	-128	40	3.12
25	-182	-138	44	3.15
25	-179	-132	47	3.15
30	-159	-125	34	3.3
30	-159	-126	33	3.32
30	-166	-142	24	3.28
30	-167	-141	26	3.32
30	-172	-131	41	3.35
30	-172	-128	44	3.4
30	-175	-132	43	3.38
30	-175	-133	42	3.38
30	-151	-129	22	3.21
30	-150	-132	18	3.21

Results & plots

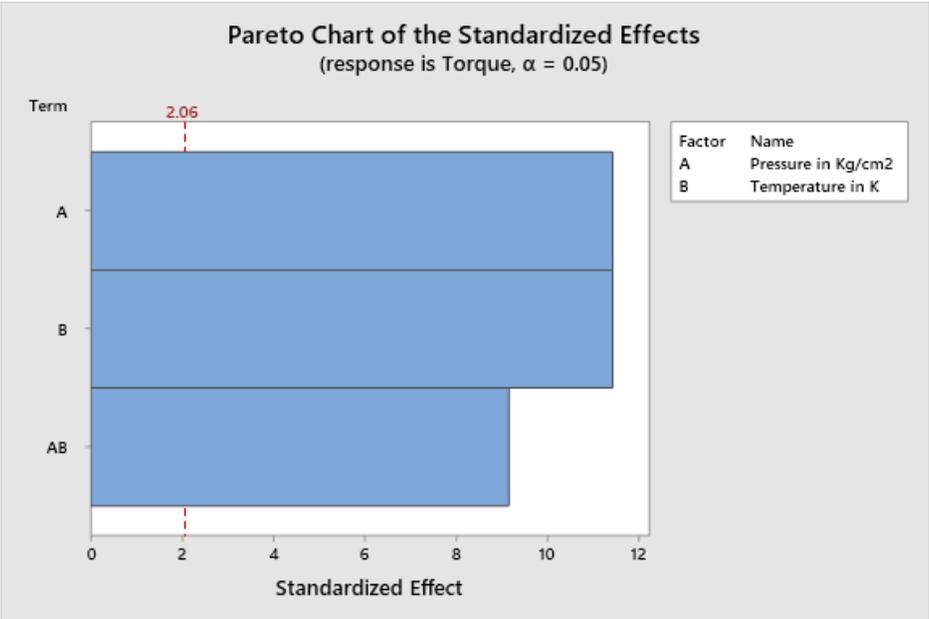


Figure 3. Pareto Chart of the standardized effects

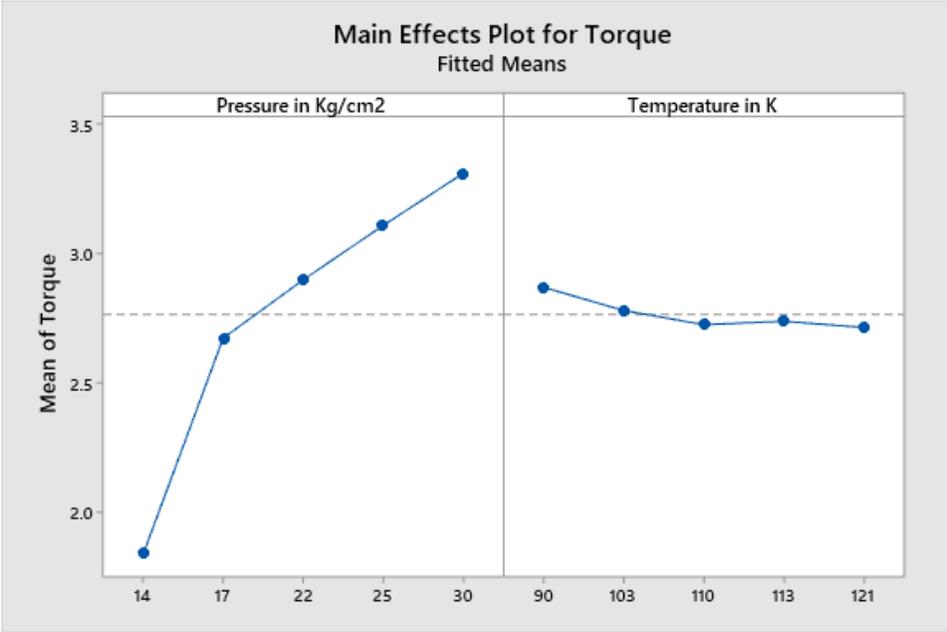


Figure 4. Effects of Pressure and Temperature as independent factors

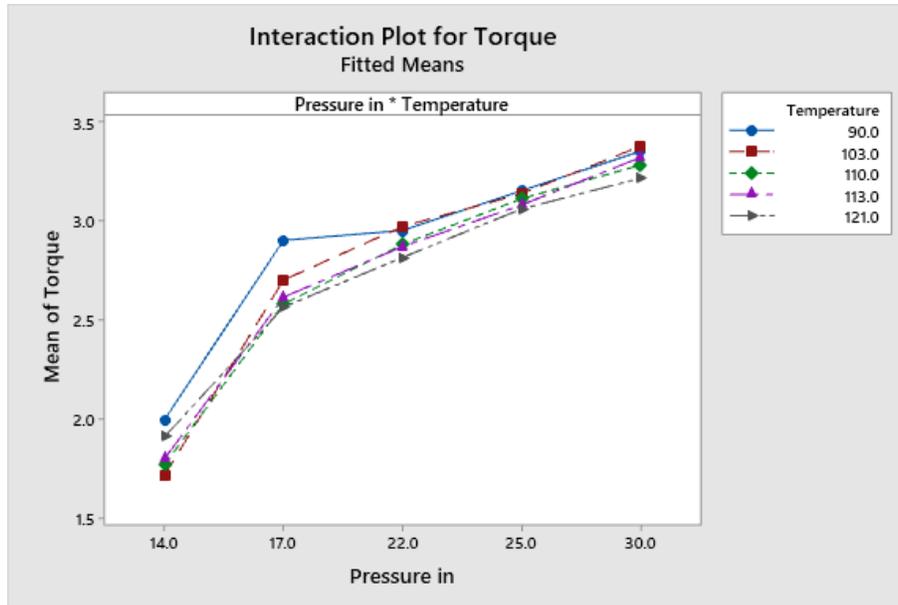


Figure 5. Effects of interaction of Pressure and Temperature

Interpretation of results

In this study, design of experiments was used as a statistical method for assessing the influence of critical process parameters on the output/response of opening torque for the DN15 Cryogenic Globe valve. For this purpose, full factorial design of two factors at five levels was built. The effect of the main factors and their interaction on the response was evaluated using regression analysis, analysis of variance and graphical analysis of the experimental design. A matrix of full factorial design on the represented 2 factors at five levels was built

Table 4 Analysis of Variance results from Minitab

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	24	13.30	0.55	876.89	0.000
Linear	8	13.13	1.64	2597.69	0.000
P (Kg/cm ²)	4	12.97	3.24	5131.38	0.000
T (K)	4	0.16	0.04	64.00	0.000
2-Way Interactions	16	0.16	0.01	16.49	0.000
P (Kg/cm ²) *T (K)	16	0.16	0.010	16.49	0.000
Error	25	0.015	0.00063		
Total	49	13.31			

Table 5 Coefficients table from Minitab

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2.76	0.0035	777.55	0.000	
P (Kg/cm ²)					
14	-0.92	0.007	-130.29	0.000	1.60
17	-0.092	0.007	-12.99	0.000	1.60
22	0.13	0.007	18.65	0.000	1.60
25	0.34	0.007	48.18	0.000	1.60
T (K)					
90	0.10	0.007	14.71	0.000	1.60
103	0.014	0.007	2.05	0.051	1.60
110	-0.014	0.007	-5.68	0.000	1.60
113	-0.027	0.007	-3.85	0.001	1.60
P (Kg/cm ²) *T (K)					
14 90	0.052	0.014	3.68	0.001	2.56
14 103	-0.13	0.014	-9.68	0.000	2.56
14 110	-0.027	0.014	-1.94	0.064	2.56
14 113	-0.01	0.014	-0.75	0.46	2.56
17 90	0.12	0.014	8.68	0.000	2.56
17 103	0.013	0.014	0.94	0.35	2.56
17 110	-0.051	0.014	-3.63	0.001	2.56
17 113	-0.029	0.014	-2.08	0.048	2.56
22 90	-0.051	0.014	-3.63	0.001	2.56
22 103	0.058	0.014	4.11	0.000	2.56
22 110	0.023	0.014	1.65	0.11	2.56
22 113	0.0004	0.014	0.03	0.97	2.56
25 90	-0.06	0.014	-4.33	0.000	2.56
25 103	0.013	0.014	0.94	0.35	2.56
25 110	0.043	0.014	3.05	0.005	2.56
25 113	0.0004	0.014	0.03	0.97	2.56

Main effects of the response from the factors including the interaction is studied by a bar graphic known as Pareto Chart. It is a graphical representation for assessing the effects of the main factors and their interactions on the response sorted by their absolute size. Both the two factors including the interaction have statistical significance on the response.

From the values of standardized effects and factors in there, it could be seen that relative effect of factors A & B i.e. pressure and temperature are more to the factor AB. It could be derived from the Pareto chart that the opening torque value depends on individual factors and has less dependency on both of them interactive to each other.

From Data by ANOVA, regarding the general model, we noted the following important characteristic Temperature 103 K, interactive factors 14 110, 14 113, 17 103, 22 110, 22 113, 25 103, 25 113 looks less significant as P-value for these combinations is greater than 0.05.

The coefficient of determination R^2 , which shows the proportional variation in the response explained by independent variables in the linear regression model is 0.9988 and the adjusted coefficient of determination is 0.9977. The value of R^2 is close to 1 reveals that there is considerable linear relationship between the factors and the response. The value of R^2 demonstrates that with more than 99 % confidence the change in response can be explained with the variables in the model. There is some slight difference between R^2 and R^2 adj values, which shows that some insignificant conditions were included in the model.

As stated above, 8 insignificant factors (including the interactive factors) are identified.

The final empirical outcome after eliminating these factors in Minitab is given below.

$$\begin{aligned} \text{Torque} = & 2.76 - 0.90 \text{ Pressure in Kg/cm}^2_{14} \\ & - 0.09 \text{ Pressure in Kg/cm}^2_{17} \\ & + 0.12 \text{ Pressure in Kg/cm}^2_{22} + 0.33 \text{ Pressure in Kg/cm}^2_{25} \\ & + 0.54 \text{ Pressure in Kg/cm}^2_{30} \\ & + 0.10 \text{ Temperature in K}_{90} \\ & + 0.0009 \text{ Temperature in K}_{103} \\ & - 0.03 \text{ Temperature in K}_{110} \\ & - 0.012 \text{ Temperature in K}_{113} \\ & - 0.05 \text{ Temperature in K}_{121} \end{aligned}$$

ANALYTICAL APPROACH

As per the analytical methodology, torque, Q , required to affect the valve closure is addition of Q_a , Q_b , and Q_c , Pearson [2] where

Q_a = torque required to impart the total axial force generated by pressure at valve inlet

Q_b = torque required to overcome the frictional resistance to rotate the spindle

Q_c = torque required to overcome the resistance by the gland packing grip

$$Q_a = \frac{Pt.pt}{2\pi\eta} \quad (6)$$

Where,

Pt = Total axial force

pt = True pitch (lead) of spindle screw thread

η = Efficiency of Screw Thread

$$Q_b = \mu_c . Pt . rm \quad (7)$$

Where,

μ_c = Coefficient of friction between spindle and mating threaded bush

rm = Mean radius of screw thread

$$Q_c = 2 . \mu_s . ls . ds^2 . P \quad (8)$$

Where,

μ_s = Coefficient of friction between spindle and gland packing

l_s = Packing length

d_s = Spindle diameter

P = Working pressure

Table 6 Torque values from analytical approach

Torque, Nm	Pressure @ 22 Kg/cm² (2.15 MPa)	Pressure @ 30 Kg/cm² (2.94 MPa)
Q_a	0.95	1.29
Q_b	1.04	1.42
Q_c	0.72	0.99
Total torque Q	2.71	3.70
Net Opening torque, Q_b+Q_c	1.76	2.41

DISCUSSIONS

The reader may observe that net opening torque is principally the addition of Q_b and Q_c and the globe valve considered possess under-the-plug flow design which do not oppose the pressure inlet.

Among the three types, torque required to overcome friction between spindle and threaded bush is the highest. It also increases with the pressure value at the valve inlet. For instance, there is an increase of around 37 % of the total torque required when pressure increased from 22 Kg/cm² (2.15 MPa) to 30 kg/cm² (2.94 MPa) at same temperature.

The reason being the frictional surface contact within the two metal parts (spindle and threaded bush) with coefficient of friction equals 0.40.

Total experimental torque required to overcome the net frictional force for 22 Kg/cm² (2.15 MPa) at 110 K is 2.88 Nm which increases to 3.28 Nm at same temperature. However, the experimental values of net torque decrease by few percentages when the temperature is increased which reasons for the relieving in the thermal stresses which may have developed relatively lower temperature.

The analytical calculations and valve design are driven by the Maximum allowable working pressure, MAWP, of the industrial process and the pipeline on which these valves would be mounted. Since the MAWP is 5 MPa, therefore the valve design is holistically designed analytically on 5 MPa.

Juxtaposing analytical with experimental values of net opening torque at cryogenic conditions, it is observed that experimentally torque values are higher than analytical values by factor of 1.67 for 22 Kg/cm² (2.15 MPa) and 0.40 for 30 Kg/cm² (2.94 MPa) respectively.

As mentioned in the earlier text, the reader may identify that the Handwheel diameter is designed not only to justify the analytical values of torque. Its design is also not limited to assumptions that

the torque values at cryogenic temperatures may be greater than what analytically calculated at ambient conditions. The design of the handwheel is assumed to bear the rising torque in case there are some foreign particles inside the threads between the spindle and the threaded bush which thereby increases the overall frictional contact area. The effect seen on overall torque with the frictional torque at thread area (Spindle /threaded bush) is the largest.

FUTURE WORK

The future scope of the project lies in numerical methodologies to correlate the experimental and analytical approach to help the valve designer to take informed decision with the optimized cost. Also, the future research scope envisaged to reduce and nullify the assumptions considered which includes coefficient of friction to surface roughness analysis. Another approach could be is to study the correlation between thermal gradient developed due to actual surface roughness.

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