IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 14, Issue 5 Ver. V (Sep. - Oct. 2017), PP 31-40
www.iosrjournals.org

Mathematical Method for Designing the Profile of the Plug of Horizontal Globe Valve for Required Inherent Flow Characteristics

Utsav Patel[1], Jignesh Muchhadia[2], Kashyap Patel[3], Vishal Advani[4]
[1,2,3,4]*(Mechanical Engineering, Vishwakarma Government Engineering College, India)*

Abstract: *In Industries it is essential to have precise and accurate control on the flow of fluid at various operations as per requirement for optimum and efficient working of plant. This can be achieved by proper valve sizing and accurate plug design as per the required flow characteristics. Here we have a developed a method to obtain the plug profile required to have the desired fluid flow characteristics depending on type of fluid and flow parameters. In this method, a random plug shape with size in accordance with size of valve (DN50) is taken. Using the modeling and CFD Analysis software, fluid flow analysis is done with proper input parameters at multiple plug location between fully open and closed condition. Pressure drop is obtained as a result at all the points, which gives the empirical relation between valve flow co-efficient Cv and fluid flow area. Using the theoretical equation of Cv for equal percentage valve, required values of Cv are obtained at various lift positions of plug to get equal percentage flow characteristics. Now using the empirical equation and required values of Cv at various lift points required flow area is obtained at the respective lift position of plug, which gives the shape of plug required for having the equal percentage flow characteristics.*
Thus, by using this method the plug shape can be generated according to required flow characteristics.
Keywords: *Computational Fluid Dynamics (CFD), Equal percentage flow characteristics, Globe Valve, Inherent characteristics, Plug profile of a globe valve*

Date of Submission: 24 -10-2017 Date of acceptance: 04-11-2017

I. Introduction

Valves control the flow of fluid, a simple but such an essential function it serves. Many types of valves such as ball valve, butterfly valve, plug valve, spherical valve, gate valve, pinch valve, globe valve, fixed cone valve, etc. are being used for various applications all over the world, the globe valve stands out among all due to full closing & throttling features, shorter opening and less closing time due to shorter stroke, etc. All these possible due to the provision of plug's geometry, which not only gives us accurate flow control, but an opportunity to obtain various flow characteristics.

The globe valve has mainly three inherent characteristics [3]

1) Linear Characteristics
2) Equal Percentage Characteristics
3) Quick Opening Characteristics

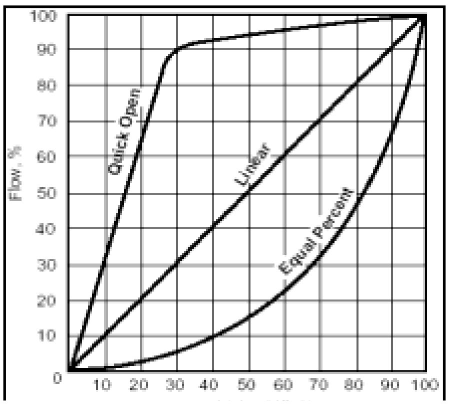


Figure [1]

Plug Design

The above mentioned characteristics heavily depend upon plug's geometry. The figure below illustrates the shape of the plug for desired characteristics. It is worth to note that the shape of the plug is designed after consideration of pressure drop across it, flow rate, property of the fluid used, etc. and after mathematical and fluid dynamics solutions the exact shape of the plug is obtained for desired characteristics. Different size of plugs shown in figure [2]

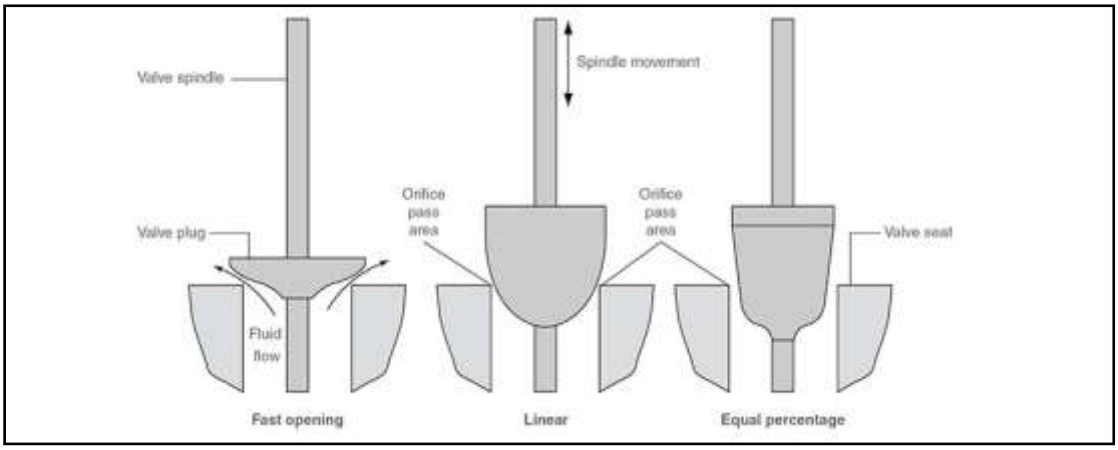


Figure [2]

Problem Summary

In industrial applications, the valves are required to perform on one of above stated flow characteristics without sacrificing the accuracy beyond certain point. Hence, as far as globe valve is concerned, the accuracy of flow control depends heavily on the shape of the plug. As stated previously, a plug has to be designed considering so many variables and assumptions, that there are no conventional methods for designing them.

AIM and Objective

Since, the fluid flow faces many fixed as well as varying restrictions, in order to measure the pressure drop, the Computational Fluid Dynamics (CFD) software helps to calculate as well as visualize distribution of pressure, temperature, velocity, etc. CFD helps to solve fluid dynamics problems with help of powerful processors so we don’t have to solve countless iteration by numerical methods. Although assumptions have to be made and the solutions are very near to accurate, but the purpose is served as CFD analysis gives us the extreme parameter’s analysis.

Here, with help of CFD and basic mathematical relations, a new method is introduced for shape of the plug to achieve desired characteristic.

II. Definitions

Flow Co-efficient: The number of US gallons of water per minute at 60F that will flow through a valve with a pressure drop of one psi.

$$C_v = Q\sqrt{\frac{SG}{\Delta P}}$$ .... Equation [1][3]

Where:
Cv =Flow coefficient or flow capacity rating of valve.
Q = Rate of flow (US gallons per minute).
SG = Specific gravity of fluid (Water = 1).
ΔP = Pressure drop across valve (psi).

Characteristics of Valve: What it represents is, the relation between flow rates through valve as the ‘stem’ travels from 0 to 100%, i.e. full close to open condition. There are mainly two characteristics, which are defined below.

a) **Inherent Flow Characteristics**: That defines the theoretical relationship between 'valve opening' and flow rate under constant pressure drop conditions.

There are mainly three inherent characteristics, which are defined below.

(i) **Linear Characteristics**: Valves in which flow rate increases linearly with lift of plug are said to be having linear flow characteristics. [Figure [1]]

(ii) **Equal percentage**: These valves have a valve plug shaped so that each increment in valve lift increases the flow rate by a certain percentage of the previous flow. It provides precise throttling control through lower portion of the travel range and rapidly increasing capacity as the valve plug nears the wind open position. [Figure [1]]

$C_v = C_{v\,max}\ R^{\left(\frac{x}{X}-1\right)}$ .... Equation [2]

(iii) **Quick opening**: The fast opening characteristics 'valve plug' will give a large change in flow rate for a small valve lift from the closed position. For example, a valve lift 60% may result in an orifice pass area and flowrate up to 90% of its maximum potential. [Figure [1]]

(b) **Installed Flow Characteristics**: The relationship between the flow rate and the closure member travel (plug) as it is moved from the closed position to rated travel as the pressure drop across the valve is influenced by the varying process conditions.

III. Modeling and Analysis

In the whole process of designing and analyzing we considered DN50 horizontal globe valve, the selected valve finds its application at many places. In the process of designing the horizontal globe valve we used following design considerations.

- As the project is confined within fluid control only, any consideration regarding stresses[5] is not considered in designing procedure.
- The valve body is designed internally to reduce the additional and useless redirection of fluid, resulting in reduced eddies generation, and reduced pressure drop.
- The inlet and outlet pipes are taken considerably long to generate uniformity of parameters along area.
- The seat is taken of 50mm diameter. i.e. DN 50
- The total lift of plug is taken of 32mm which is accordance with industrial standards for plug design. i.e. 0 mm at full closer and 32 mm upwards at full opening[3]
- All the edges and corners are rounded of reducing (to reduce) the sudden changes in the direction of flow, resulting in reduced turbulence and eddy.
- At the initial stage of plug design, the random shape of plug should be linear as shown in figure [4] to encounter less errors as the first step of obtaining equal percentage characteristics is to obtain corresponding linear characteristics.

Summary of Steps: Design of random plug design > Obtaining desirable theoretical shape of plug's equation for equal percentage flow > Designing equal percentage plug > Comparison of actual characteristics to ideal characteristics

Definition of Random plug design: A shape of plug preferably linear as shown in figure below on which the further design process will take part. Our goal is to obtain equal percentage characteristics, but in order to obtain it, we need a reference plug of any kind which will bear the further modifications. In mathematical sense, a random plug is a plug which will have its own characteristics, but will undergo modified characteristics which will be of equal percentage characteristic in nature. Here, preferably random plug shape should be linear as it represents linear characteristics and easy to design, takes less time to analyse.

The 3D modeling of the valve is done in CREO 3.0. (Student Version) The final model of DN50 horizontal globe valve and randomly selected plug are shown in figure [3], figure [4], figure [5] and figure [6].

Figure [3]

Figure [4]

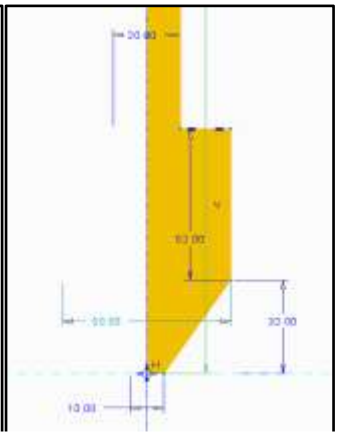


Figure [5]

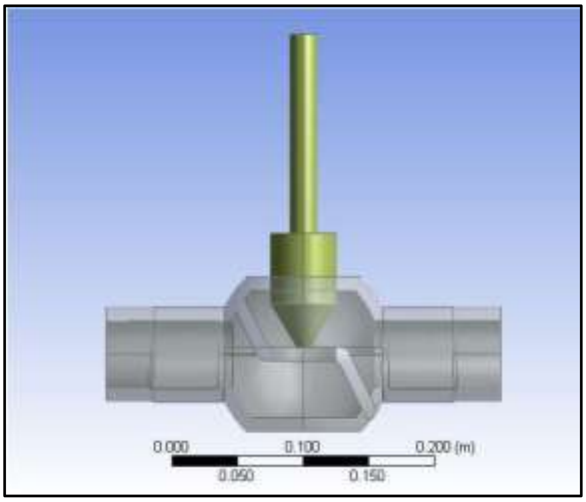


Figure [6]

After designing the valve, CFD Analysis of the valve is performed at multiple positions of plug between completely closed i.e. (0 mm lift) and completely open (32 mm lift) conditions, to obtain the respective pressure drops between entry and exit points. While performing CFD analysis, it is extremely important to extract fluid flow domain [1] from the 3D model. We extract fluid flow domain from the valve with the help of ansys design modeler. The fluid flow domain is shown in figure [7].

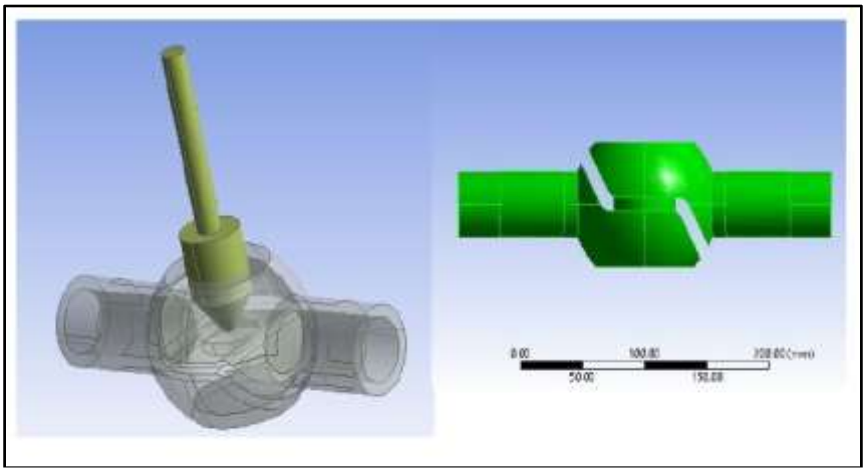


Figure [7]

Following are the parameters[4] considered while performing CFD Analysis[1]

- Turbulence Model[1]: K epsilon
- Heat Transfer Model[1],[6]: Isothermal
- Solver Control: Min. Convergence=E-04 or Max. Iteration 100

Boundary Conditions[4]

- Inlet: Mass Flow Rate=1.38 kg/s
- Outlet: Pressure Drop=0.5 MPa

Assumptions

- No Phase change during fluid flow.
- No change in properties during fluid flow.
- Heat Transfer Model: Isothermal (4.5K).
- Working fluid: Helium (Pure Substance).
- Thermodynamic State: Liquid.

Material Properties

- Molar Mass - 4.003 g/mol
- Density 136.8 kg/m^3
- Specific Heat Capacity[6] (Constant Pressure) 3954.63 J/kgK
- Dynamic Viscosity[4] 3.85272e^{-06} Pa-S
- Thermal Expansibility[4] 0.450436 /K

Meshing of Model[1],[5]

Since fluid flow region of Globe valve is complex geometry itself, the role of proper meshing cannot be ignored. Compromise has to be made between accurate results and faster rate of convergence since too many nodes will take up large portion of storage of computer and too much accurate result is necessarily not needed. Hence suitable grid generation will save lot of time and desired result will be delivered. That is, refined tetrahedral cells around 'plug' and 'seat' of the valve since, large pressure drop takes place in those region, Sweep Meshing for pipes will take advantage of symmetricity, inflation layer in order to take care of boundary layer near wall. After the analysis, few mesh methods are changed in order to ensure "Grid Independent" result.
After generating mesh, these parameters [1] must be checked in Statistics of **ANSYS** details view panel before further proceeding.

- Number of Nodes and Elements
- Aspect Ratio (Should be close to value of 1)
- Jacobean Ratio (Should be close to value of 1)
- Skewness (Should be close to value of 0.5)

Applying the above mentioned parameters in CFD solver [1], analysis is performed at various lift positions, with a convergence level of E-04. The Cross section images of pressure contour and velocity streamlines of valve at 4 mm lift, obtained from CFD analysis are shown below in figure [8] and figure [9].

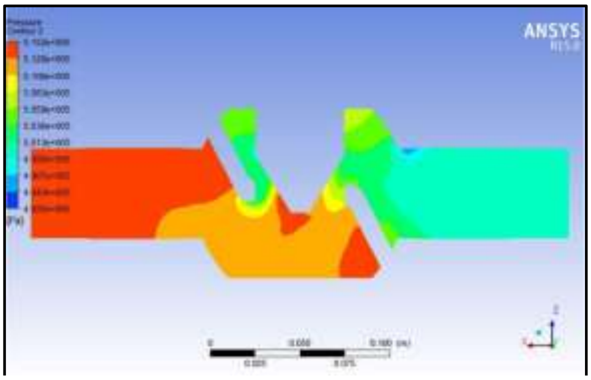


Figure [8]

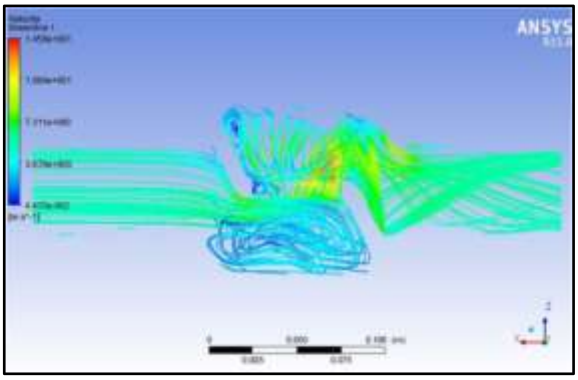


Figure [9]

IV. Working Principle and Method Verification

Working Principle: The new proposed methodology for designing the plug of the control valve for the given inherent characteristics mainly depends upon the invariability of valve flow co-efficient at particular valve configuration. The results shown in the table [1] show that the value of valve flow co-efficient at particular valve opening remains constant for different flow parameters. This implies that the valve flow co-efficient remains constant for given fluid flow area, which is shown in Table [1].

Sr. No.	Lift	Mass Flowrate	Inlet pressure P1 (in Kpa)	Outlet Pressure P2 (in Kpa)	P1-P2	Cv
1	12	1.38	507.686	500	7.686	56.2
2	12	1	504.05	500	4.05	56.1
3	12	0.5	501.015	500	1.015	56.01
4	12	0.2	500.163	500	0.163	56

Table [1]

From the table [1] it can be inferred that the value of Cv fairly remains constant at particular valve lift for the given set of flow parameters.

In the new proposed methodology, for any valve body, random plug shape is chosen and CFD analysis at different valve openings is done. The results obtained by performing the CFD analysis at different valve openings help to establish a relation between valve flow co-efficient and fluid flow area.

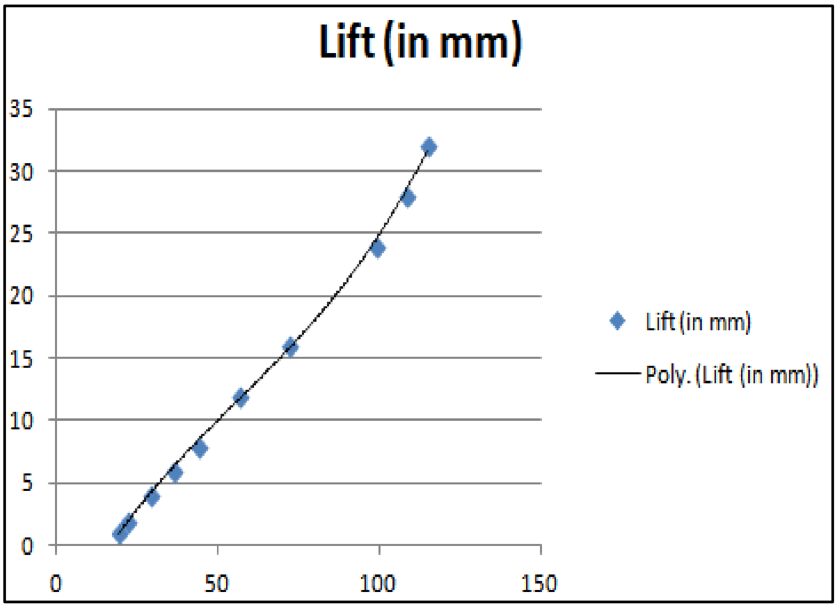
The obtained relationship between the valve flow co-efficient and fluid flow area is used to design the shape of the valve plug for given inherent characteristics. In the process, for the required inherent characteristics, values of valve flow co-efficient at different valve openings are obtained from the theoretical equation for that inherent characteristic. The obtained values of valve flow co-efficient at different valve openings are assigned the value of fluid flow area from the established relationship between valve flow co-efficient and fluid flow area, and by applying the same process at various valve openings a curve for the required inherent characteristics can be obtained.

Method Verification: As stated in the working principle, firstly, we analyzed the DN50 horizontal globe valve with a random plug at various valve openings ranging from 0 mm- 32mm. As the results of analysis, we obtained the value of inlet pressure for given mass flow rate and outlet pressure, which are the boundary conditions for the performed analysis, at various position of plug. From the obtained results the values of valve flow co-efficient at different valve openings are calculated by the equation of valve flow co-efficient [equation [1]]. The obtained results are stated in the table [2] given below.

Sr. No.	Lift (in mm)	Mass Flowrate (in Kg/s)	Inlet Pressure P1 (Kpa)	Outlet Pressure P2 (Kpa)	P1-P2 (in Kpa)	Cv	Lift (in mm)
1	1	1.38	565.174	500	65.174	19.3	1
2	2	1.38	550.617	500	50.617	21.9	2
3	4	1.38	528.668	500	28.668	29.1	4
4	6	1.38	518.525	500	18.525	36.2	6
5	8	1.38	512.712	500	12.712	43.7	8
6	12	1.38	507.686	500	7.686	56.2	12
7	16	1.38	504.722	500	4.722	71.7	16
8	24	1.38	502.492	500	2.492	98.7	24
9	28	1.38	502.081	500	2.081	108	28
10	32	1.38	501.835	500	1.835	115	32

Table [2]

Now, from the obtained data, a Cv versus Lift plot is generated as shown in Graph [1].The trend line function of MS-excel is used to fit the curve in the plot. The empirical relationship between valve lift and valve flow co-efficient is given by the equation [2]. The line well fits the data with RMS error of 0.646994.



Graph [1]

$$LIFT = 0.0007 * c_v^2 + 0.2214 * c_v - 3.0904 \qquad \text{.................. Equation [3]}$$

From the geometry of randomly selected plug shown in figure [10], the equation of relationship between radius of plug and valve flow co-efficient can be obtained, which is given by equation [4].

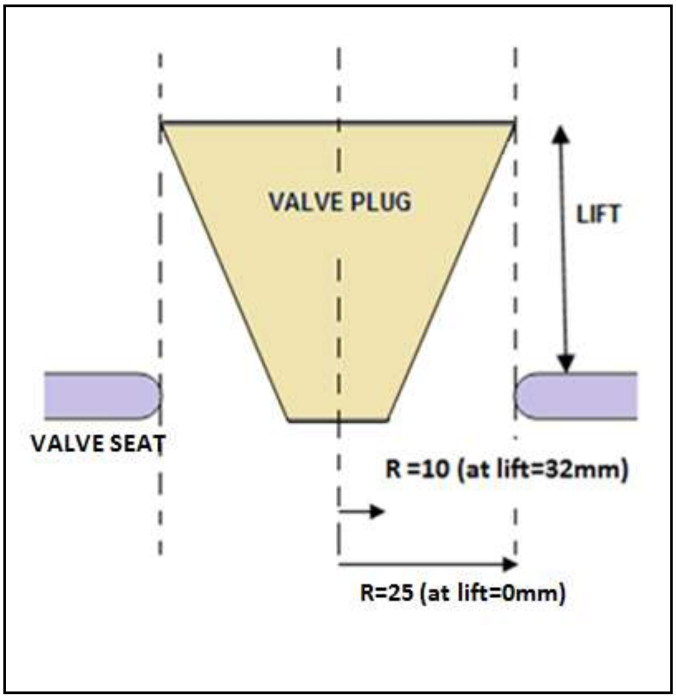


Figure [10]

$$\text{Slope} = \frac{lift}{25 - R} = \frac{32}{20}$$

$$lift = (25 - R) * \left({}^{32}/_{20}\right)$$

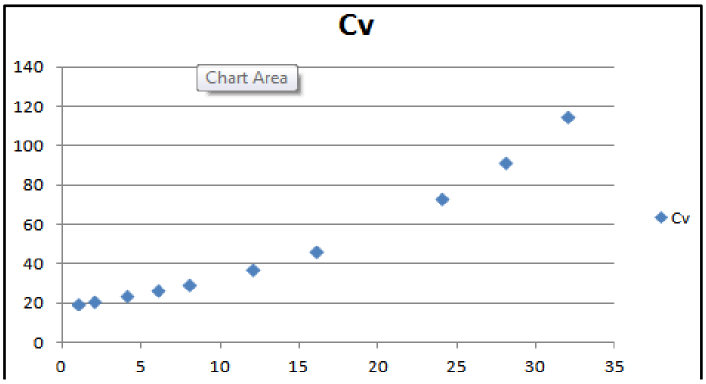
$$(25 - R) * \left({}^{32}/_{20}\right) = 0.0007 * c_v^2 + 0.2214 * c_v - 3.0904$$

$$R = 27.0602 - 0.0004375 * C_v^2 - 0.138375 * C_v \quad \text{......Equation [4]}$$

Now, for the required equal percentage horizontal glob valve with Cv_{max} =115 and Cv_{min}= 19.3, values of valve flow co-efficient at different valve lifts can be obtained by the theoretical equation for equal percentage which is given by equation [2], as shown in table [3]. The graph of Cv versus lift is shown in graph [2].

lift	Cv
1	20.40722
2	21.57779
4	24.12421
6	26.97113
8	30.15401
12	37.69096
16	47.11176
24	73.60607
28	92.00379
32	115

Table [3]



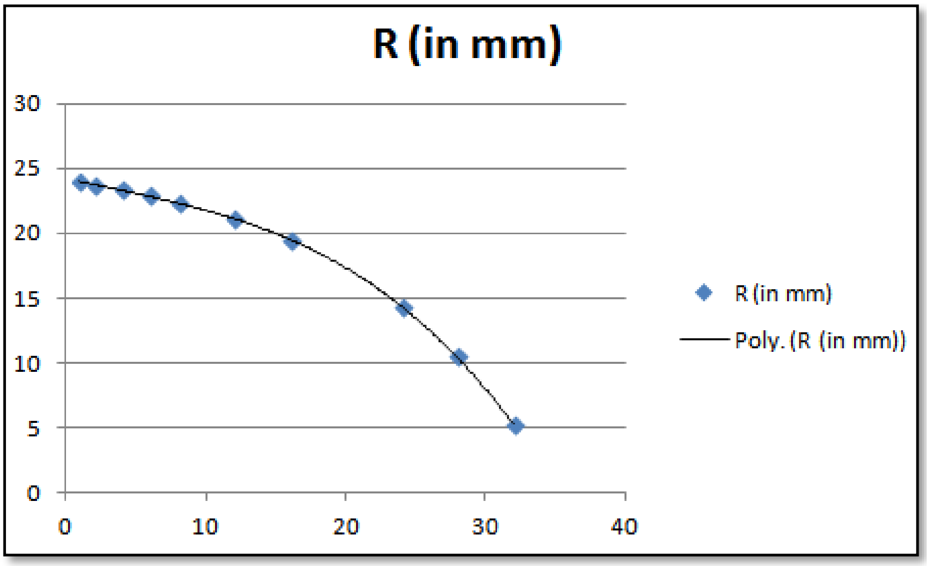
Graph [2]

It has been proven from the table [1] that at particular valve lift Cv remains constant, so for each value of the theoretical obtained valve flow co-efficient, value of radius can be safely assigned by the equation [4], the value of radius for each value of valve flow co-efficient are shown in table [4].

lift	Cv	R (in mm)
1	20.40722	23.925
2	21.57779	23.741
4	24.12421	23.338
6	26.97113	22.881
8	30.15401	22.361
12	37.69096	21.094
16	47.11176	19.441
24	73.60607	14.375
28	92.00379	10.497
32	115	5.232

Table [4]

From the data given in table [4] it is possible to fit a curve with the help of trend line function of Ms-Excel, from various polynomial curves, 3rd order polynomial best fits the data with RMS error of 0.130767. The radius versus lift plot and the third order polynomial are given below.



Graph [3]

$Lift = -0.0005 * C_v^3 + 0.0049 * C_v^2 - 0.2457 * C_v + 24.226$ ....Equation [5]

The obtained 3rd order equation [5] gives the profile for required equal percentage globe valve. The plug with the given profile is modelled in CREO 3.0. The plug is shown in figure [11].

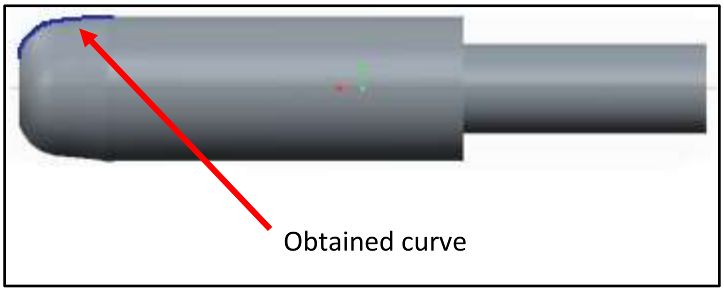


Figure [11]

Now with the newly obtained plug, the horizontal globe valve is again analyzed in CFD at various valve openings. The Cross section images of pressure contour and velocity streamlines of valve at 16 mm lift, obtained from CFD analysis are shown below in figure [12] and figure [13].

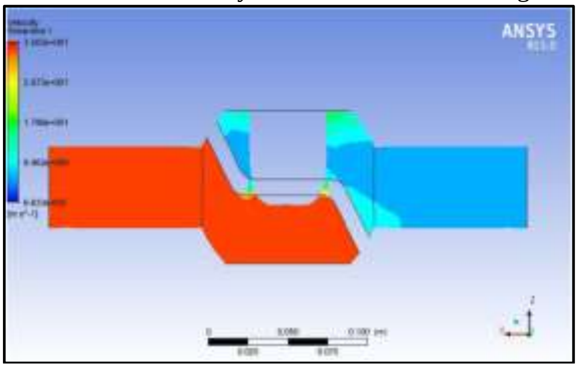


Figure [12]

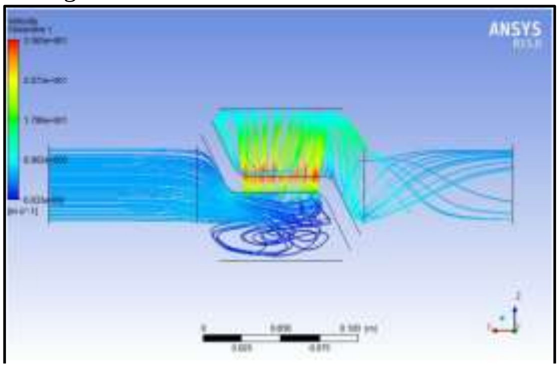


Figure [13]

As the results of analysis, we obtained the value of inlet pressure for given mass flow rate and outlet pressure, which are the boundary conditions for the performed analysis, at various position of plug. From the obtained results the values of valve flow co-efficient at different valve openings are calculated by the equation of valve flow co-efficient [1]. The obtained results are stated in the table given below in table [5].

Sr. No.	Lift (in mm)	Mass Flowrate (in Kg/s)	Inlet Pressure P1 (Kpa)	Outlet Pressure P2 (Kpa)	P1-P2 (in Kpa)	Cv
1	1	1.38	556.172	500	56.172	20.789
2	2	1.38	541.333	500	41.333	24.235
3	4	1.38	535.044	500	35.044	26.32
4	6	1.38	530.412	500	30.412	28.2536
5	8	1.38	526.699	500	26.699	30.154
6	12	1.38	519.576	500	19.576	35.215
7	16	1.38	511.534	500	11.534	45.878
8	24	1.38	504.612	500	4.612	72.548
9	28	1.38	502.87	500	2.87	91.96
10	32	1.38	501.835	500	1.835	115

Table [5]

The comparison between theoretical and obtained values of valve flow co-efficient for equal percentage globe valve is shown in the table [6] below. The value of RMS error is 1.5.

Sr. No	lift	Theoratical Cv	Obtained Cv
1	1	20.40722375	20.789
2	2	21.57778968	24.235
3	4	24.12420524	26.32
4	6	26.97112573	28.2536
5	8	30.15401403	30.154
6	12	37.69096446	35.215
7	16	47.1117643	45.878
8	24	73.60606561	72.548
9	28	92.00379093	91.96
10	32	115	115

Table [6]

V. Conclusion

The results well establish the newly proposed methodology for horizontal globe valve. The methodology can be used to accurately design the profile for given inherent characteristics in less number of design iterations. The method is applicable to wide range of inherent characteristics.

Future work scope

The proposed methodology can be experimentally established by performing the process on real system. Also by executing the method in real life situation, large data set can be easily obtained and accuracy of method can be improved by removing the problem of under fitting and over fitting of the curve. The method is currently verified on horizontal globe valve, so in future the verification can be done on other types of globe valve. In advanced analysis, dynamic mesh settings are encouraged to use with transient flow analysis conditions. Although this will require higher amount of data storage requirement and computational capabilities.

Acknowledgement

We wish to make sincere thanks to Mr. Pratik M Patel (ENGINEER-SD (Mechanical), ITER-India) for his valuable guidance and encouragement.

References

[1] Computational Fluid Dynamics the Basics with Applications by Jr., John D. Anderson
[2] Valves, Piping & Pipelines Handbook by T. Christopher Dickenson F.I. Mgt
[3] “Valve Basics and Sizing Information” by Johnsons
[4] Fox and Mcdonald's Introduction to Fluid Mechanics
[5] "Design and Analysis of a High Pressure Globe Valve" by Prabha Kurian, C R Krishnamurthy, Rajesh R in
[6] International Journal of Emerging Technology and Advanced Engineering, Volume 4, Issue 10, October 2014
[7] Fundamentals of Heat and Mass Transfer by Frank P. Incropera

Utsav Patel Mathematical Method for Designing the Profile of the Plug of Horizontal Globe Valve for Required Inherent Flow Characteristics.” IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 14, no. 5, 2017, pp. 31-40.