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Characterization of Cryogenic Globe valve for advanced launch Vehicles

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Abstract: **Liquid Propellant servicing of any propulsion systems is very critical due to hazardous nature of fluids and safety involved in handling. For any successful launch mission, fluid servicing, especially with respect to cryogenic servicing is very critical due to complex preparation, chilling, filling, and pre-launch operations involved. During fluid servicing of launch vehicles, critical process parameters such as pressure, temperature and flow rate are required to be attained with in the specified tolerance limits to meet launch lift-off requirements. Cryogenic propellants have a very low boiling point and low latent heat of evaporation due to which pressure and flow control is very challenging. Hence, it is very important to predict the actual performance characteristics of the flow control valve for different stroke lengths and for different plug profiles and select the optimum plug to suit to process conditions. Flow coefficient Cv is of primary interest in predicting the valve performance during its operation. This paper attempts to predict performance characteristics of a cryogenic globe valve used for flow control of Liquid Oxygen flow using computational fluid dynamics (CFD). Valves having different valve capacity factors were considered for evaluation of performance characteristics and derived the pressure and velocity contours inside the valve. The performance of this control valve installed in the Cryogenic fluid circuits have been independently evaluated for various process flow conditions and suitability of the valve has been verified for optimum flow conditions. The results of the computational analysis are found to be in close agreement with experimental tests**

Index Terms— **Cryogenic propellants, Control Valve flow Coefficient v, CFD.**

I. INTRODUCTION

Control valves are used in process industries for control of fluid flow. The selection of the control valve type, design and plug plays a vital role for optimum performance of the control valve. Control valves when employed for cryogenic service require special design considerations due to special properties of the cryofluids such as very low boiling point, low latent heat of vaporisation and very high liquid to gas volumetric expansion ratios of about 800. Hence Control valves used in Cryogenic Systems are of special construction and are provided with bellow sealed to minimise stem leakage, extended stem for avoiding frost and vacuum jacketed type for minimisation of heat in leak. Heat in leak is an important parameter as it controls the phase of the fluid across the valve and cryogenic piping circuit. One of the most common types of Cryogenic control valves is the single seat globe valve. It consists of three main components: body, plug, stem group and spring return diaphragm actuator. The body of the control valve houses the plug assembly which is made up of the plug and seat, and stem group. The actuator positions the plug inside the valve for achieving tight shut off characteristics against inlet fluid.

Prediction of actual performance of the control valves requires robust trials for various process conditions with actual cryogenic fluids which is a cumbersome. Now with the use of Computational fluid dynamics (CFD) techniques prediction of valve performance to suit a process application can be done much faster. Also the pressure and velocity contours inside the valve and the sonic characteristics can be predicted, which the experiments hardly provide. Even otherwise, experimental results validated with theoretical predictions using techniques like CFD analysis because of fluid flow through complex geometry during flow through the valve.

The present work focusses on the evaluation of performance characterisation of cryogenic control valve design of the plug which is responsible for the inherent valve flow characteristics. For a process system requires different flow conditions and which require different shapes of the plug to achieve optimum flow control.

Selection of Valve and Valve characteristics for Cryogenic flow control applications

Globe valves with bellow sealing extended stem and vacuum jacketed are used in cryogenic systems where good throttling characteristics and low seat leakage are desired. Cryogenic ball valves allow quick, quarter turn on-off operation and have poor throttling characteristics. The valve bellow seal provided limits the stem leakage to a value of 1 x 10-8 mbarlit/sec and seat leak is limited to 1 x 10-6 mbarlit/sec for all cryogenic applications.

Valve Characteristic

The valve characteristic is a plot of the flow coefficient against percentage opening of the valve and represents the rate of change of flow with different valve openings. The two most commonly used control valve characteristics are linear and equal percentage. For Linear characteristic valve, flow rate increases linearly with valve plug travel, and for equal percentage for equal percentage, where flow rate increases exponentially with valve plug travel. Both of these characteristics are shown in Fig. 1. Linear characteristics are used especially for level control applications and equal percentage characteristics are for having better flow controllability at lower flow rates particularly for cryogenic applications.

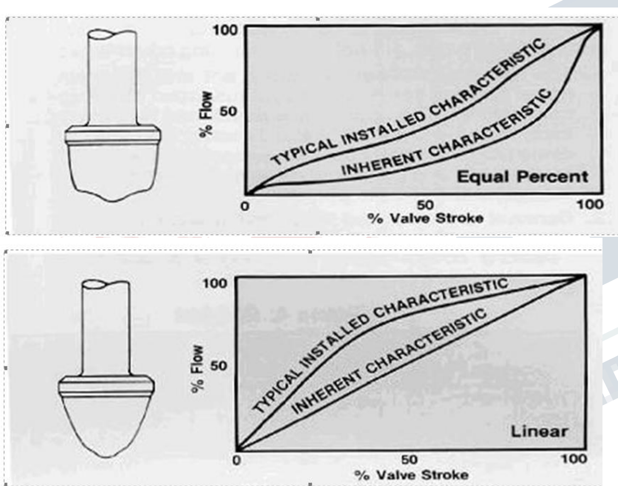

Fig. 1. Control valve equal percentage and linear flow characteristics

2.0 Control Valve Sizing for Flow

Two important control valve parameters are the overall flow coefficient C_v and the relative valve capacity factor C_d. In general, the calculation methods for *Cv* are a function of the valve Reynolds number, Re*v* .
The flow coefficient *Cv* is a measure of the valve capacity. It is given by the ISA standard S75.01 @14# for incompressible fully turbulent, noncavitating, and no flashing flow as

$$C_v = 11.6q\sqrt{\frac{G_f}{\Delta P}}$$

Where

C_v is the flow coefficient of the valve at full opening
ΔP is the pressure drop across the valve.
q is the nominal flow rate across the valve.
G_f is the Specific gravity of the flowing fluid.

This equation is applicable for fully turbulent flows for which the valve parameters are independent of the Reynolds number. In reality due to complex geometry of the globe valve, Reynolds number Re_v is usually acceptable parameter and for calculation of the same, the circular diameter of the orifice was correlated to control valve Cv and effective diameter of the orifice considering experimentally determined correction factors as recommended by ISA is

$$Re_v = \frac{76{,}000 F_d q}{\upsilon F_L^{1/2} C_v^{1/2}} \left[\frac{F_L^2 C_v^2}{(0.00214) D^4} + 1 \right]^{1/4}$$

where

Fd is a value that accounts for the effect of the valve geometry
FL is a value that relates the overall pressure drop across valve Relative valve capacity factor relative to pipe nominal diameter is given by

$$C_{VN} = C_d * (d/25.4)^{\wedge 2}$$

Where for single port globe valve C_d = 11 d is the nominal diameter of the valve.

The following are the control valve nominal diameters and flow coefficients C_v are considered for evaluation of performance characteristics.

Table 1

Parameter	Valve Size	Valve Cv
Valve A	25.4mm(1inch) Seat Dia :25mm	08
Valve B	25.4mm(1inch) Seat Dia :25mm	13

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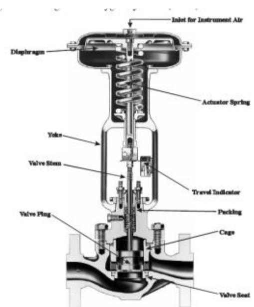

Fig.2. Control valve

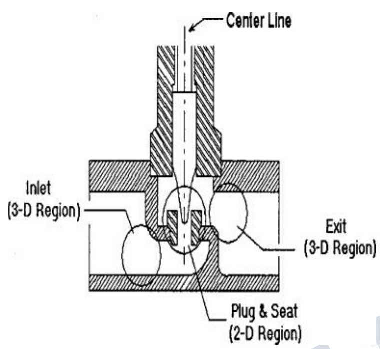

Fig 3. Different regions of a Control valve

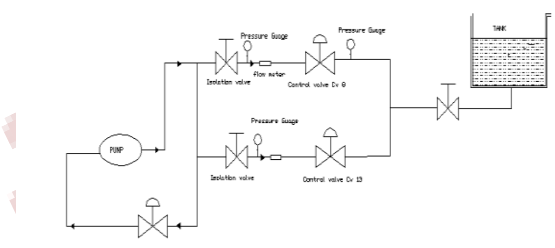

Fig 4. Schematic Diaphragm of experimental Set up

3.0 Experimental Set up

A series of experiments were performed on a 25 mm globe valve with plug details given in Table-1 to validate the simulation results. The schematic of the experimental test setup is shown in Fig.4. It is an open loop re-circulating system which consists of variable frequency centrifugal pump, control valves to be performance tested and isolation valves to control and bypass the flow. Liquid oxygen with a maximum flow rate of 20m3/hr and at a 15 bar pressure is filled in to stage tanks at controlled flow rate of 0.3-1.0kg/sec. The flow control is done by control valves installed in the circuit. Initial pump stabilisation is done by circulating liquid oxygen in the pass path without filling the stage. Once flow stabilises, first path with Control valve (Cv=8) is chilled with a flow rate of 0.3kg/sec and once temperature of the line is less than 90K, the control valve opening is increased in steps of 5% and the corresponding flow rate is measured and recorded. Similar procedure is followed for the second path with control valve of Cv13 also. The differential pressure flow meter is used for measurement of the flow rate across the control valve and pressure sensor is used for measurement of pressure at inlet and outlet of Control valve.

4.0 CFD Model for analysis

Cryogenic globe style control valves were modelled using CFD analysis. The control valves having equal percentage plug profiles having flow coefficients of 8 and 13 of 25NB size are modelled. Two configurations of 20% and 30% openings were simulated independently for both the plug contours. CFD analysis is carried out using commercial Fluent V14.5. Velocity and pressure profiles are derived for both the configurations for comparison. For the purpose of simulation an inlet pressure of 9.5 bar is considered with outlet vent boundary condition. Realisable k-ε model is used for turbulent modelling. Simulation is run to get the convergence in the order of 10-5 the results,

CV:8 Control valve with 20% opening

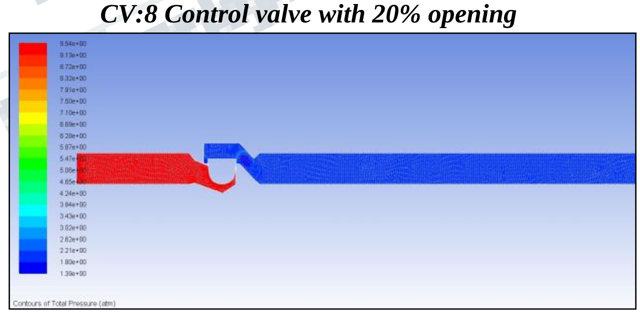

Fig 5. CV:8=Pressure Profile with 20% opening

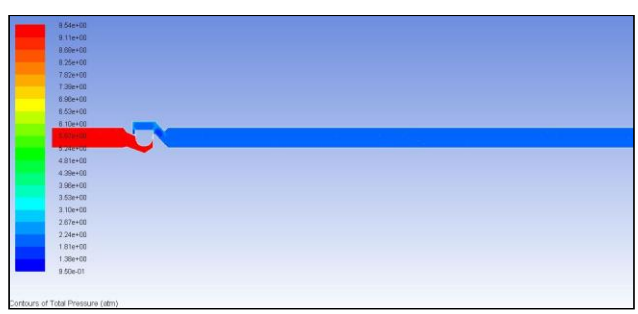

Fig 6. CV:8= Pressure Profile with 30% opening

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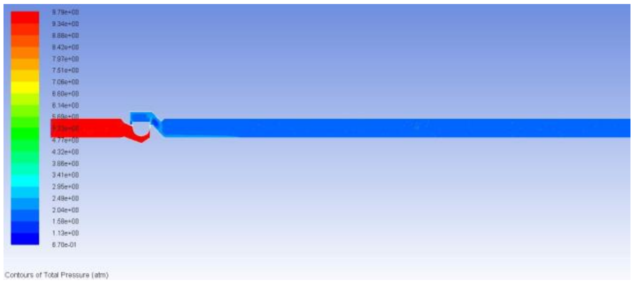

Fig 7. CV:13 Pressure Profile with 20% opening

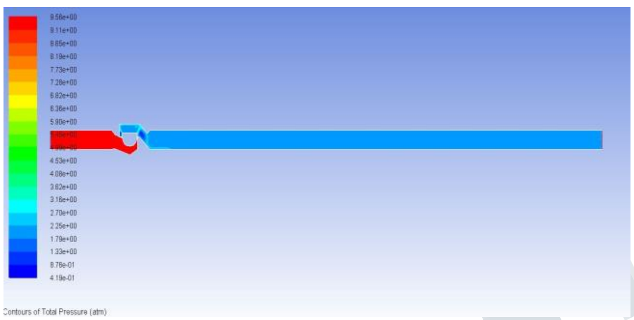

Fig 7. CV:13 Pressure Profile with 30% opening

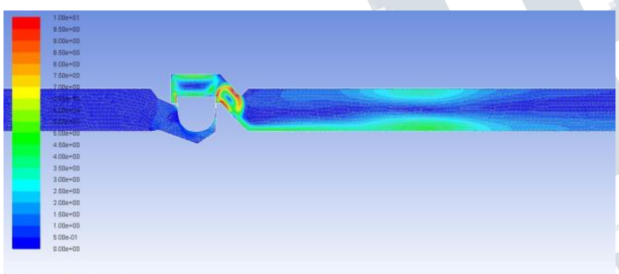

Fig 8. CV:8 Velocity Profile with 20% opening

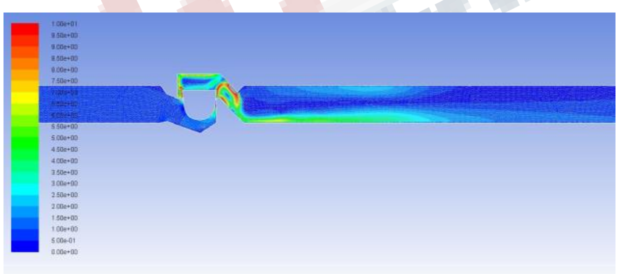

Fig 9. CV:8 Velocity Profile with 30% opening

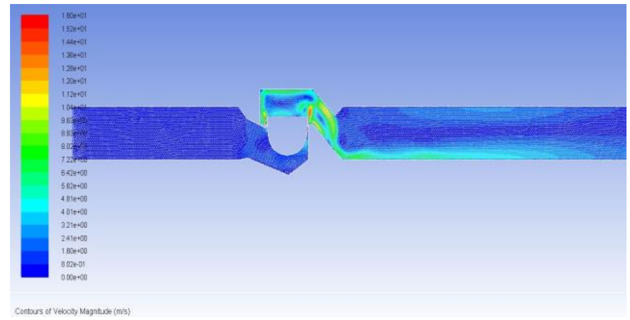

Fig 10. CV:13 Velocity Profile with 20% opening

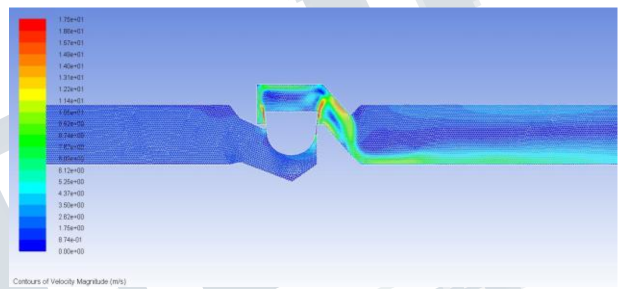

Fig 11. CV:13 Velocity Profile with 30% opening

5.0Results and discussions

For the analysis results, it is found that the theoretically predicted inherent valve characteristic of the valves with different flow coefficients is in close agreement with experimentally determined inherent valve characteristic. As predicted increment in pressure values are observed with higher opening percentages and higher Cv at the downstream of the valve. Flow stabilisation occurred at a distance of approximately greater than 5D as indicated by the velocity contours. Pressure profiles indicated there is no occurrence of cavitation across the valve geometry for all the cases of openings for both the plug contours. The velocity contours indicated that at valve lower openings, pressure disturbances and rotational fluid flow is observed immediately at the downstream region of the plug and valve body. At higher valve openings and for higher flow coefficients, the intensity of pressure disturbances and rotational fluids flow are mitigated.

NOMENCLATURE

Cd = relative valve capacity factor (m3/hr/kPa0.5/mm2)
Cv = valve flow coefficient (m3/hr/kPa0.5)
D = internal diameter of pipe (mm)
Fd = valve style modifier (dimensionless)

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FL = pressure recovery factor (dimensionless)
Gf = liquid specific gravity (dimensionless)
ΔP = Pressure drop (kPa)
q = volumetric flow rate (m3/hr)
Rev = valve Reynolds number (dimensionless)
V = Kinematic Viscosity-(Centistokes)

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