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Design and development of a control valve plug for precise control and measurement of cryogenic flow

Austin Grake, Nusair Hasan*, Jonathon Howard, Venkatarao Ganni

Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan, USA

*E-mail: hasann@frib.msu.edu

Abstract. Cryogenic control valves are one of the critical components of a cryogenic fluid distribution system. In many cases, control of the cryogenic process flow needs to be directly or indirectly accompanied by accurate flow measurement. However, this can be challenging due to the measurement device introducing heat in-leak, potential thermal hydraulic instability, design complexities and cost. A well calibrated control valve with precisely known stroke vs. flow coefficient profile has the potential to serve as a cryogenic flow measurement device. A valve flow test bench is developed for the calibration and characterization of cryogenic control valve plugs. For applications in helium cryogenic distribution systems, low flow (C_V<1.0) control valve plugs with equal percent characteristics and high rangeability (R≥10) are of interest. Several control valve plug profiles for a specific cryogenic control valve (available domestically in US) are designed using an analytical model. These include equal percent profiles with different rangeability, flow coefficient as well as hybrid profiles with variable rangeability. Flow characteristics of these control valve plugs are evaluated using the valve flow test bench, under ambient conditions. A comparative analysis of the measurement accuracy of the proposed set-up against advertised accuracy of trivial flow measurement devices are presented.

1. Background

Cryogenic control valves are critical components in process systems, where they regulate fluid flow and pressure by modulating a flow control plug within an orifice. These valves consist of key elements including the actuator (manual, pneumatic or electrical), bonnet, stem, flow control plug, and seat, all housed within a robust valve body. In globe valve configurations, the flow control plug's shape - usually conical or cylindrical, directly influences flow characteristics. Cryogenic conditions introduce complexities due to the extreme operating temperatures. To reduce thermal conduction from ambient surroundings to the cryogenic fluid, designs often incorporate elongated stems and thermal intercept collars. Various components of a typical cryogenic valve are shown in fig. 1 (left). Flow capacity of a control valve is characterized by the valve flow coefficient (C_v). In general, a characteristic curve for the variation of the flow coefficient against the valve stroke is used to fully define the behaviour of the valve. Many different plug flow characteristics can be achieved, but the following three are very common - quick-open, linear, or equal-percentage flow characteristic. An equal percentage flow characteristic means that the valve flow rate changes by the same percentage for each increment of valve stroke (position). This flow profile is particularly critical in systems requiring fine control at low flow rates and wide dynamic range, such as in large-scale cryogenic systems. For a valve with well-known flow characteristic, it is feasible to estimate the mass flow across the valve knowing the stroke, inlet process conditions, and the pressure differential. In such a case, it can be utilized as a flow measurement device.

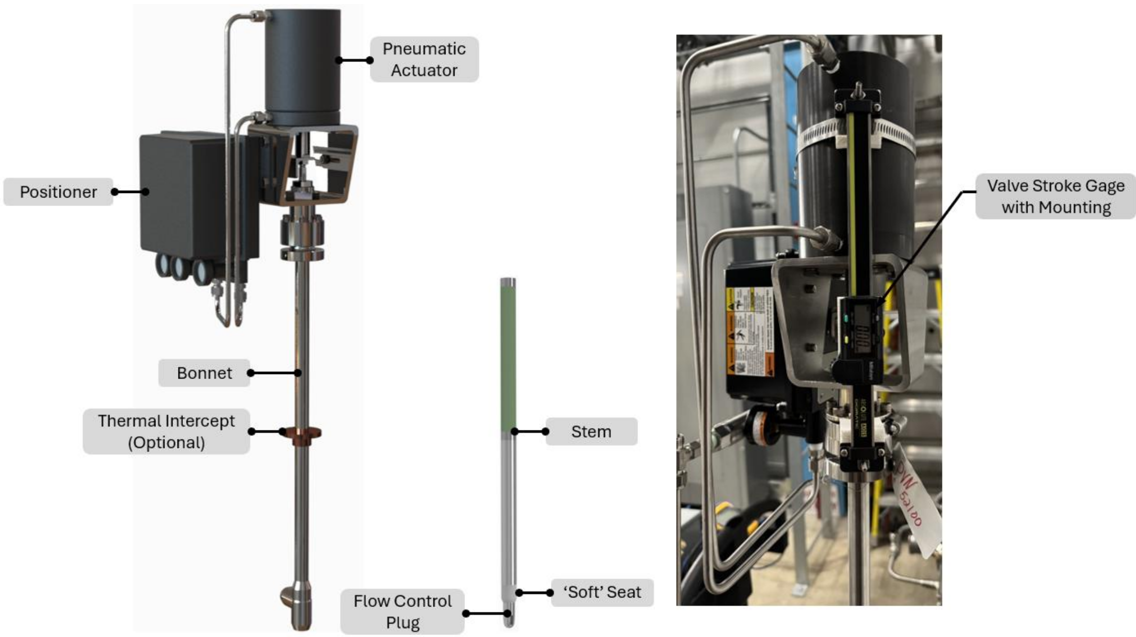

Figure 1. Typical cryogenic valve with a pneumatic actuator (left), elongated valve stem and flow control plug (center), and valve stroke gage mounted on the actuator (right).

The present study focuses on the development and experimental characterization of cryogenic control valve plugs with equal percent and hybrid flow characteristics. By combining analytical modelling and experimental validation, the work aims to provide a methodology for cryogenic valve plug development. An application of the developed valve flow characteristics curves in estimation of cryogenic flow measurement is also demonstrated.

2. Development of equal percent flow characteristic plug

To achieve precise control of flow, especially under varying operating conditions, an analytical model was developed to design valve plugs with equal percentage flow characteristics. This model relates plug geometry directly to flow performance parameters including maximum flow coefficient ($C_{V,m}$), rangeability (R), and non-dimensional stroke position (ξ).

The analytical design of the equal percent flow plug begins with the incompressible flow coefficient, alternatively defined as the volumetric flow rate of the fluid that can pass through an opening with a defined pressure drop. It is specifically defined as the amount of water at 60°F (in gallons) that can flow through the valve per minute when there is a pressure drop of 1 psi across the valve [1] as shown in Eqn. (1).

$$C_v = \frac{Q[gpm]}{\sqrt{\Delta P[psi]}} \quad (1)$$

The equational definitions of rangeability and equal percentage characteristics [2, 3] are provided in eqns. (3) and (4) from the differential equal percent characteristic in eqn. (2).

$$\frac{\partial \mathrm{C}_v}{\partial \xi} = \mathrm{a} \cdot \mathrm{C}_v \tag{2}$$

$$R = \left(\frac{C_{v,m}}{C_{v,o}}\right) \tag{3}$$

$$C_v = C_{v,m} \cdot R^{(\xi-1)} \tag{4}$$

The flow through an orifice for an incompressible fluid can be described using eqn. (5) [4]. The throat area can be described as a diameter based on the equational definitions of a circle's area. The throat diameter is comparable to the annular diameter. Based upon this, the area or diameter of the throat can be equated to the flow coefficient as seen in eqns. (1), (5), and (6). Additionally, N_{01} = 29.839 (which is required for proper unit conversion into SI units).

$$Q = (KA_t)\sqrt{\frac{2 \cdot \Delta P}{\rho}} \tag{5}$$

$$C_v = \frac{Q[gpm]}{\sqrt{\Delta p[psi]}} = N_{01} \cdot (K \cdot {D_t}^2[in^2]) \tag{6}$$

The flow coefficient can be expressed along the plug profile in terms of D_t, *i.e.* the diameter associated with the flow area between the upstream valve body wall diameter (D_o) and the plug diameter (D).

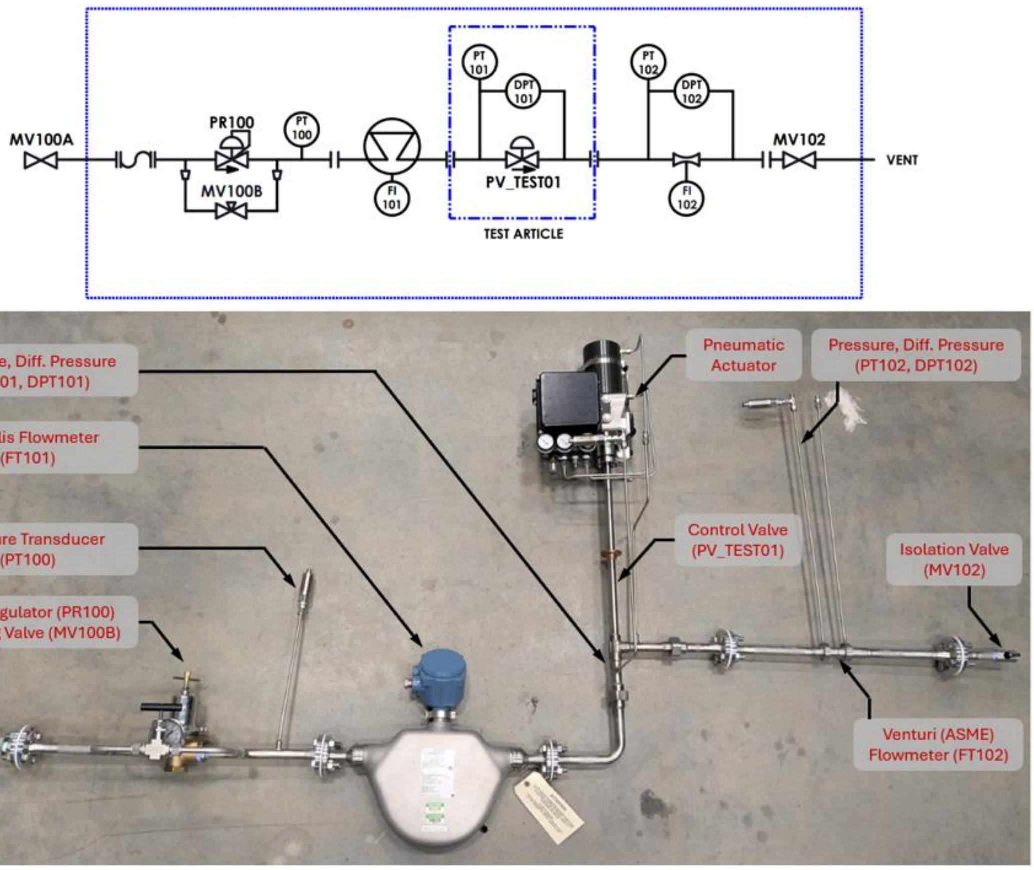

Figure 2. Schematic of the valve experimental test bench (top), and actual components and assembly of the test bench (bottom)

$$D_t = \sqrt{{D_o}^2 - D^2} \quad (7)$$

$$\Delta = D/D_o \quad (8)$$

Once the non-dimensional ratio of the plug diameter to upstream diameter is found, an equal percentage plug profile is developed in terms of the non-dimensional gap between plug and upstream valve body wall. To relate the diameter change to equal percent characteristics, the equal percent characteristic equation can be modified to include rangeability. Here C_v represents the flow coefficient anywhere along the non-dimensional opening ($0 \le \xi \le 1$) from $C_{v,o} \le C_v \le C_{v,m}$. Rearranging, C_v can be described in terms of rangeability and non-dimensional stroke. The non-dimensional change in plug diameter profile can be described non-dimensionally along ξ.

$$C_{v,m} \cdot R^{(\xi-1)} = N_{01} \cdot K \cdot {D_o}^2(1-\Delta^2) \quad (9)$$

$$\Delta = \sqrt{1 - \frac{C_{v,0}}{N_{01} \cdot K \cdot {D_o}^2} \cdot R^{\xi}} = \sqrt{1 - \frac{C_{v,m}}{N_{01} \cdot K \cdot {D_o}^2} \cdot R^{(\xi-1)}} \quad (10)$$

For the generated analytical models, the orifice size was kept constant at 0.416 in. as well as the length of the profile, which is also the length of actuation of 0.75 in. Therefore, the variation came from selecting a maximum flow coefficient, varying the base diameter (or rangeability), and generation method of the plug tip causing the length of the plug to vary. As a note, these equations are developed based on incompressible flow assumption, and all plugs developed and discussed in this paper are machined following these equations. For an in-depth explanation of these equations refer to [5]. For the specific application cases, using a valve plug profile designed for incompressible flow is valid, since the differential pressure across the valve is relatively low and flow remains un-choked. However, the realized valve plug flow coefficients are evaluated using ANSI ISA S75.01 standard [6], where corrections for compressible flow, fluid viscous effects etc. are appropriately considered. The set of ANSI ISA S75.01 equations used for the evaluation of the flow coefficients are not included in the paper for the sake of brevity.

3. Development of an experimental test bench for valve flow characterization

3.1 Experimental Test Bench for Valve Flow Characterization

A schematic of the valve experimental test bench along with the assembly of the different components are shown in fig. 2. The ANSI ISA S75.02 standard provides elaborated guidelines for the characterization of control valve flow coefficients and associated testing. This standard is closely followed for the development of the test bench shown. Following ANSI ISA S75.02, dry nitrogen gas at room temperature is used for all the tests performed. The overall nitrogen flow through the valve is controlled by a flow regulator (PR100) and a metering valve (MV100B). Two different flow measurement devices are used for calibration and accuracy. The valve is actuated at different strokes (between 5-100%) and the mass flow rate ($\dot{m}$), pressure drop across the valve (Δp), inlet temperature (T), and inlet pressure (p) are recorded.

3.2 Uncertainty Analysis of Flow Coefficient using Experimental Test Bench Measurements

The measurement accuracy of each of the components is listed in table 1. The RMS uncertainty method [7], using the derivative of the flow coefficient of a compressible non-choked flow with respect to each independent variable was used as shown in eqn. (13). In this case based upon ISA75.01 standards of the flow coefficient calculation, a derivative of flow coefficient (C_V) with respect to Δp, T, p, $\dot{m}$ were calculated from eqns. (11) and (13).

Table 1. List of instrumentations used and their measurement accuracies

Instrument Type	Vendor	Fluid Service	Range	Accuracy (±)
Digital Caliper	Mitutoyo	[-]	0-150 mm	.01 mm of Reading
Pressure Trans.	Emerson Rosemount 3051 Series	Nitrogen	0 to 7 bar	.04% of Span
Temperature Sensor	Omega / T-Type Thermocouple Sensor	Nitrogen	33.15 K - 623.15 K	0.5% of Reading
Diff. Pressure Trans.	Emerson Rosemount 3051 Series	Nitrogen	0 to 621 mbar	.10% of Span
Coriolis Flow Meter	Emerson Micromotion	Nitrogen	0-25 g/s	0.25% of Reading
Venturi	Flowdyne	Nitrogen	[-]	Estimated; eqn. [11]

$$\sigma_{\dot{m},venturi} = \sqrt{\left(\frac{\partial \dot{m}}{\partial DPT102}\sigma_{DPT102}\right)^2 + \left(\frac{\partial \dot{m}}{\partial \rho}\sigma_{\rho}\right)^2} \tag{11}$$

$$C_v = (W)\left(N_6 * \left(1 - \frac{\Delta P}{P * 3 * F_\gamma * x_T}\right)\sqrt{\Delta P \rho_1}\right)^{-1} \tag{12}$$

$$\sigma_{C_v} = \sqrt{\left(\frac{\partial C_v}{\partial \dot{m}}\sigma_{\dot{m}}\right)^2 + \left(\frac{\partial C_v}{\partial P}\sigma_{PT101}\right)^2 + \left(\frac{\partial C_v}{\partial \Delta P}\sigma_{DPT101}\right)^2 + \left(\frac{\partial C_v}{\partial T}\sigma_{T101}\right)^2} \tag{13}$$

4. Experimental characterization of equal percent and hybrid valve plugs

Several characteristic dimensions of a control valve plug are shown in fig. 3 (left). Two different types of valves are designed following the methodology described in Sec. 3. These are the equal percent (*'A-series*') and hybrid ('B-series'). Based on specific process and application requirements, an equal percent valve plug with a max. flow coefficient of 0.3 is developed to fit an existing valve body with a fixed orifice diameter (D_o). Multiple plugs with variable base diameter (D_{base}) are developed to determine a practical machining tolerance (i.e. difference between D_o and D_{base}). These series of valve plug with an equal percent flow characteristic and max. flow coefficient of 0.3 are named as 'A-series' (A1, A2, A3, A4). A similar methodology is followed for developing another type of control plugs with a hybrid flow characteristic. These have a hybrid equal percent flow characteristic developed by merging the plug profiles with a max. flow coefficient of 0.3 and 0.8 at approx. 50% of valve plug stroke. These hybrid series of valve plugs are named as 'B-series' (B1, B2, B3). The intended design characteristics of both types of plugs are shown in fig. 3 (right).

For each of the plugs developed (A1, A2, A3, A4, B1, B2, B3), flow coefficients are estimated based on experimentally obtained parameters and using the ANSI ISA S75.01 set of equations.

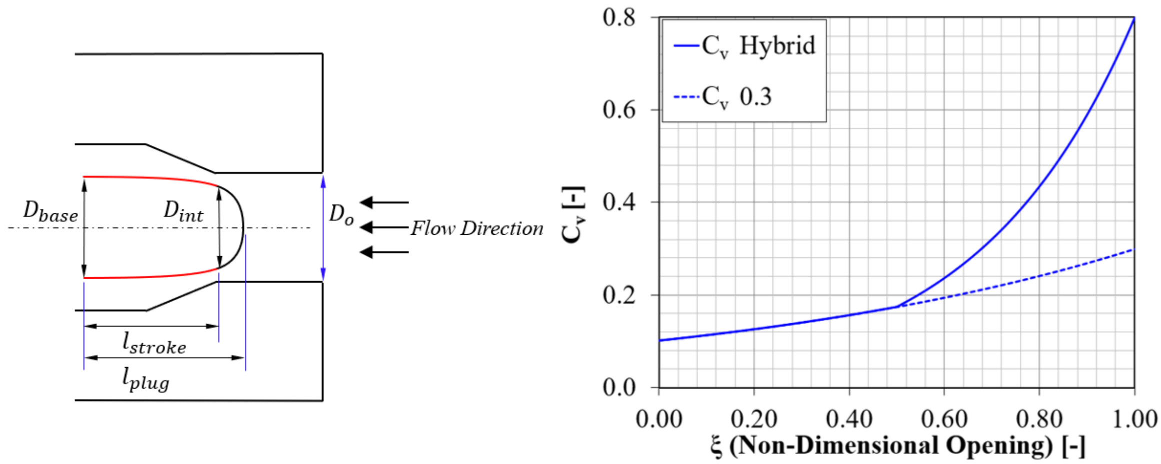

Figure 3. Schematic of a control valve plug with different characteristic dimensions (left), and intended flow characteristics for the two different types of plugs developed

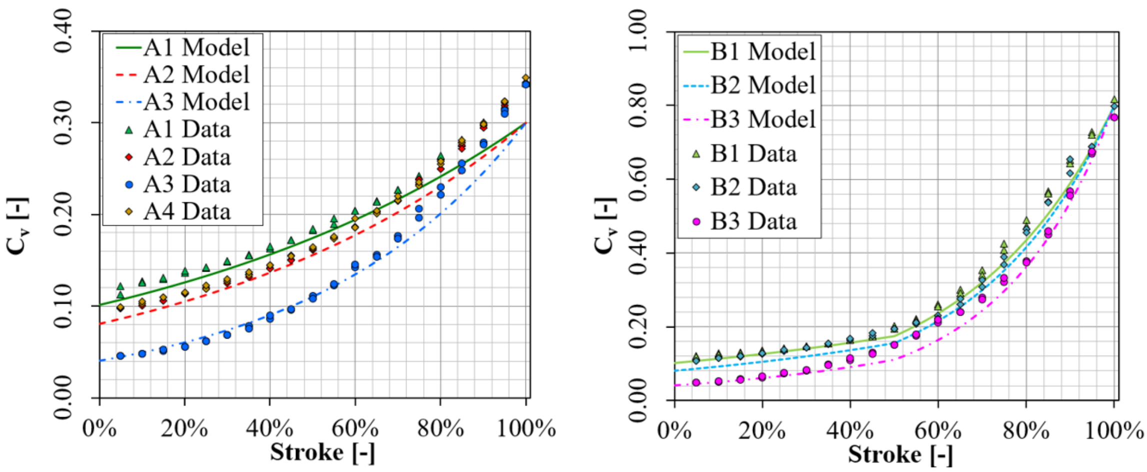

Figure 4. Experimentally determined valve plug flow coefficients as a function of the plug stroke for 'A-series' (left) and 'B-series' plugs developed

The valve plug characteristics (flow coefficient as a function of the stroke) for each of these plugs are presented in fig. 4. For the equal percent valve plugs ('A-series'), the maximum analytically designed flow coefficient ($C_{V,m}$) reasonably matched the experimental maximum flow coefficient ($C_{V,m,exp}$) for each design tested. While there was slight variation between the model and the data (<16%) above 80% stroke, the plugs followed an equal percentage characteristic within the normal operating range (30-80%). The discrepancy in the measured versus design maximum C_v is likely attributed to manufacturing tolerances near the plug tip. To achieve finer resolution and greater accuracy in C_V, a completely new valve design with a reduced orifice diameter is preferred; however, this is outside the scope of this study. For the hybrid valve plugs ('B-series'), the maximum analytically designed flow coefficient ($C_{V,m}$) and the experimental maximum flow coefficient ($C_{V,m,exp}$) followed similar trends to the 'A-series.' The variation between the maximum designed and experimental C_V was less than 4%. As expected, the increase in base diameter (D_{base}) enhanced the rangeability while reducing the minimum flow coefficient. The reduced discrepancy between the measured and designed max. C_V is likely due to a steeper diameter

Table 2. List of design parameters for the valve plugs developed

Part ID [-]	$C_{v,m}$ [-]	R [-]	$C_{v,m,exp}$ [-]	R_{exp} [-]	$\ell_{stroke, measured}$ [in.]	ℓ_{plug} [in.]	D_{Base} [in.]	Character [-]
A1	0.3	3.0	0.34	2.9	0.674	0.948	0.4110	Eq %
A2	0.3	3.7	0.34	3.5	0.676	0.948	0.4120	Eq %
A3	0.3	7.4	0.34	7.5	0.676	0.946	0.4140	Eq %
A4	0.3	3.7	0.35	3.5	0.675	1.000	0.4120	Eq %
B1	0.8	7.9	0.82	6.8	0.674	0.920	0.4110	Hybrid
B2	0.8	9.9	0.80	7.4	0.671	0.919	0.4120	Hybrid
B3	0.8	19.7	0.77	16.0	0.674	0.915	0.4140	Hybrid

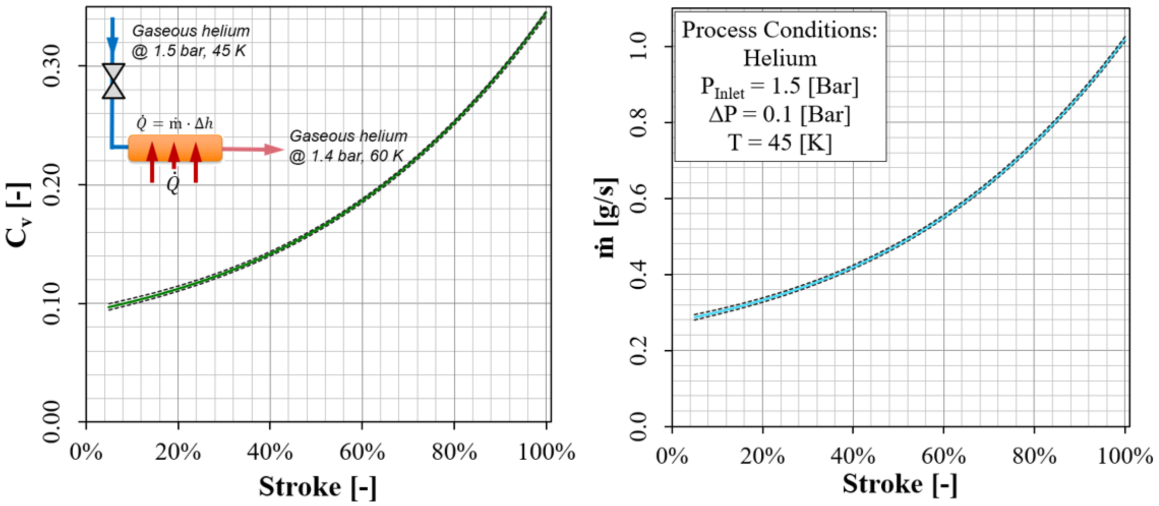

Figure 5. Valve plug (A2) flow characteristic curve with uncertainty limits established based on measurements (left), and corresponding estimated mass flow rates with uncertainty limits based on specific process conditions

gradient, which better matches the gradient near the tip. Table 2 lists a summary of the design parameters for the different valve plugs developed and characterized.

5. Application of the valve plug flow characteristics in cryogenic flow measurement

To demonstrate the applicability of the established valve flow characteristic curves (as presented in fig. 4), a specific application scenario is considered. Superconducting magnets operating at liquid helium temperatures (~4.5 K), thermal radiation shielding maintained at an elevated temperature (~40-100 K) is used to minimize heat in-leak into the liquid helium. Additionally, several cryogenic components must be thermally intercepted at this temperature for stable operation. For such an application, thermal shielding using gaseous helium at 1.5 bar, 45 K is considered. Knowing the mass flow rate of the helium from the valve characteristic curve (A2 is this example), the cooling load in this thermal shielding circuit can be determined. A simplified schematic of this circuit and the flow characteristic curve (A2 valve plug) with associated uncertainties are shown in fig. 5 (left). The experimental characterization of the A2 valve plug (flow coefficient vs. stroke) is curve-fitted to obtain the C_V at any stroke value between 5% and 100%. The maximum uncertainty in C_V characterization is observed to be approx. 6%. Given an exact process condition (helium at 1.5 bar, 45 K with a 0.1 bar differential pressure across the valve), the helium mass flow can be estimated (as shown in fig. 5 - right). The uncertainty of this mass flow calculation is similar to the C_V characterization uncertainty with a maximum uncertainty of ~6%. Knowing the exact outlet temperature (*e.g.* 60 K), the cooling load can be estimated. For a nominal operating range of the valve (40-60%), the overall uncertainty of this estimation is approx. 4%; i.e. for a nominal cooling load of 40 W, the measurement uncertainty is approx. 1.5 W. Of course, measurement uncertainties of the process parameters will negatively affect this estimation and the actual measurement uncertainty can be much greater than this value. However, for a series of superconducting magnets, adding traditional flow measurement devices to estimate individual heat in-leak is neither cost-effective nor feasible. The methodology described in this section offers a simplified approach for gross estimation of mass flow and cooling loads. Although it may not offer very high fidelity in cases where measurement uncertainties (*e.g.*, temperature, pressure, differential pressure) are unknown, it provides a relative estimation for a series of similar magnets.

6. Summary

Seven novel valve plugs were designed, fabricated, and experimentally validated to enhance the performance of helium cryogenic control valves. The analytical model developed for equal percentage and hybrid plug profiles demonstrated strong agreement with experimental data, confirming the viability of using these plug geometries to precisely control flow characteristics across the valve stroke range. Moreover, the valve plug designs addressed several key objectives: expanding the operational range of existing valve hardware, enabling the integration of multiple flow characteristics into a single valve (i.e., precise control at low stroke and high capacity at full stroke), and standardizing valve bodies for varied process needs using interchangeable plugs. This interchangeability simplifies maintenance, reduces the need for stocking multiple spare parts, and increases flexibility during system upgrades. Commercially available low-flow valves were found to be either too delicate for cryogenic service or insufficiently robust to handle thermal stress and maintain seal integrity during operation**.** The resulting plug configurations offer precise flow control capabilities for cryogenic systems and serve as viable alternatives to commercial valves. These outcomes are directly relevant to FRIB's ongoing cryogenic infrastructure development and provide a general methodology applicable to the design of cryogenic valve plugs.

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