ELECTROMAGNETIC SMART VALVES FOR CRYOGENIC APPLICATIONS

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ABSTRACT

Electromagnetic valves with smart control capability have been developed and demonstrated for use in the cold end of a Collins-style cryocooler. The toroidal geometry of the valves was developed utilizing a finite-element code and optimized for maximum opening force with minimum input current. Electromagnetic smart valves carry two primary benefits in cryogenic applications: 1) magnetic actuation eliminates the need for mechanical linkages and 2) valve timing can be modified during system cool down and in regular operation for cycle optimization.

The smart feature of these electromagnetic valves resides in controlling the flow of current into the magnetic coil. Electronics have been designed to shape the valve actuation current, limiting the residence time of magnetic energy in the winding. This feature allows control of flow through the expander via an electrical signal while dissipating less than 0.0071 J/cycle as heat into the cold end.

The electromagnetic smart valves have demonstrated reliable, controllable dynamic cycling. After 40 hours of operation, they suffered no perceptible mechanical degradation. These features enable the development of a miniaturized Collins-style cryocooler capable of removing 1 Watt of heat at 10 K.

INTRODUCTION

The machine described here is a precursor to a modular, three-stage cryocooler capable of sustaining 1 Watt of cooling at 10 Kelvin. If successful, the three-stage machine will represent a two-fold increase in efficiency over existing cryocoolers in the same class.

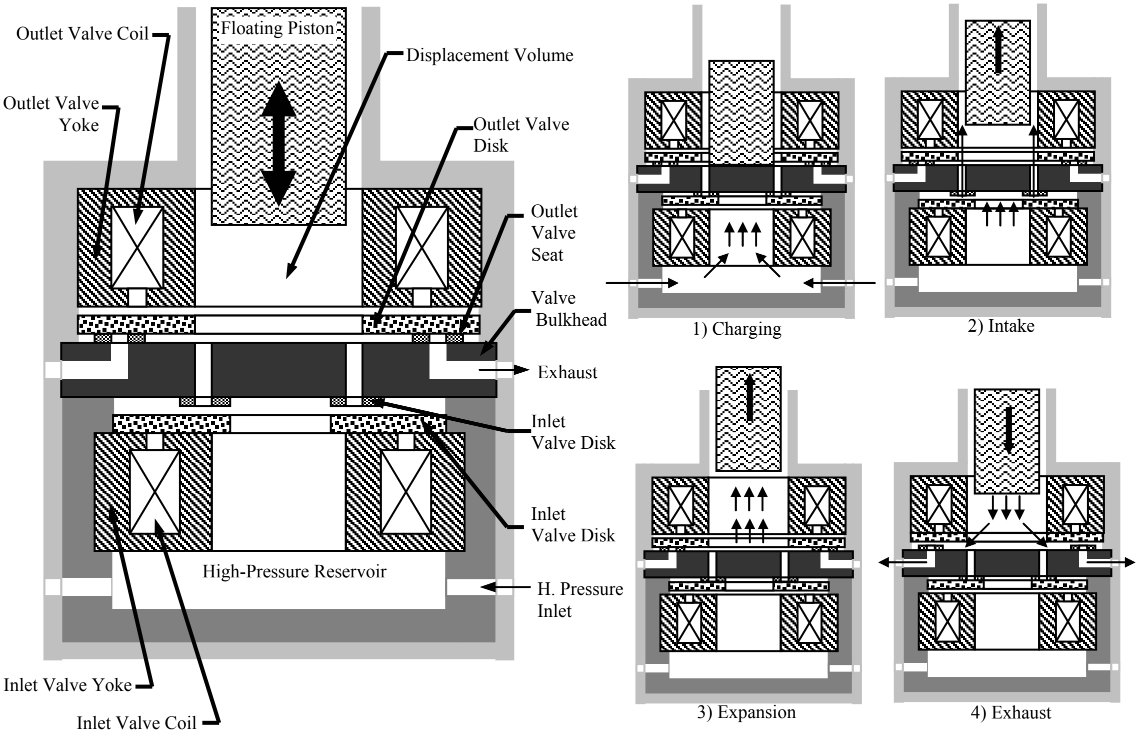
This performance is enabled by reducing the size of an industrial-scale Collins cycle cryocooler with the following benefits [1]: 1) creating a Collins cycle cooler small enough to dedicate to a single electronics package; 2) utilizing technologies impractical in larger machines, including electromechanical valves.

Miniaturizing the Collins cycle requires a cold end and expander that adiabatically expands the working fluid to drop its temperature [2]. The cryocooler's cold end, represented schematically in FIGURE 1, contains two cold valves controlled by a LabView-based data acquisition and control system. The inlet valve regulates flow from a high-pressure reservoir into the expander displacement volume. The outlet valve channels cooled working fluid out the cold end to the load. A full explanation of the miniaturized Collins cycle cryocooler is more fully discussed elsewhere [3].

HARDWARE DESCRIPTION

As pictured in FIGURE 2, each valve consists of a toroidal yoke made of Carpenter's 430FR solenoid quality steel [4]. A groove cut in the valve yoke parallel to the valve axis reduces dynamic magnetic eddies. Within the yoke, a 900-turn coil of insulated, 34-gauge copper wire is wound to create the valve coil. A pair of valve coil leads emerges from the backside of each valve yoke.

Each valve yoke actuates a thin annular disk that seals on eight Kel-F seats. The valves are situated on opposite sides of the valve bulkhead where they serve as normally closed check valves when de-energized (see FIGURE 1). In the absence of backpressure, an array of eight permanent magnets embedded in the valve bulkhead hold the valve disk on the Kel-F valve seats. These magnets also provide closing force on the valve disks in the absence of backpressure. Passages drilled through the valve bulkhead allow gas to pass through when the valve is open.



1) Charging 2) Intake 3) Expansion 4) Exhaust

FIGURE 1. Schematic of valve locations and working fluid movement in the cryocooler's cold end.

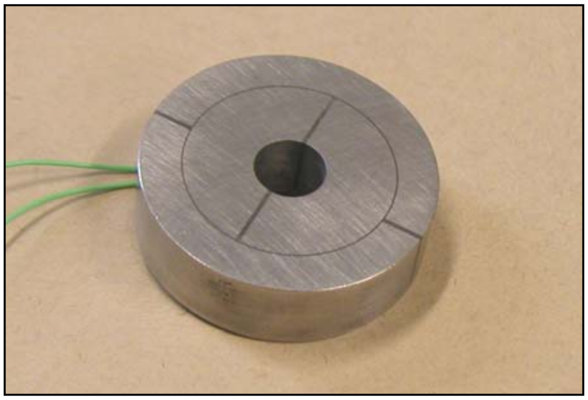


FIGURE 2. Image of the valve yoke showing a match to geometry suggested by the finite element code.

To open a valve, the copper winding is energized with current, which induces a magnetic field in the valve's axial direction. The field, magnified by the high-permeability valve yoke, draws the valve disk away from the valve seats. The valves must open against 1.7×10^6 Pa (250 psi), the maximum pressure differential in the cycle. Each valve yoke is built to generate at least 14.2 N (3.2 lbf) opening force on the valve disk in its closed position. This pull is enough to overcome the induced force on the valve disk by the pressure difference across the eight 1.143 mm (0.045 inch) diameter valve ports.

NEW VALVE DEVELOPMENT PROCESS

Analytical methods for electromagnetic actuators give the force-current relation,

$$F = \frac{\mu_o A}{2}\left(\frac{Ni}{g}\right)^2 \tag{1}$$

where the permeability of air is μ_o; A is the area normal to the flux path; Ni is the coil amp-turns; and g is the gap length between the valve yoke and valve disk [5].

We found that this relation grossly overestimates the force generated by the actuator. In cryogenic electromagnetic valve applications, high force must be achieved while minimizing power dissipation in the cold end. Equation (1) offers an order of magnitude performance estimate for three-dimensional geometries. Finite element models offer an additional level of accuracy and allow refinement in the valve design to match system requirements.

Design Development

Valve development was enabled by the Quickfield 4.3 finite element package [6]. A baseline geometry was selected to benchmark all design iterations. Shown in FIGURE 3, this geometry meets the cold end spatial constraints but not the opening force requirement.

An exhaustive exploration of the design space is impractical, and hence an evolutionary iterative process was adopted. Each potential improvement was exercised through a range of reasonable values. In general, the geometry with the most favorable force output to current input was carried into the next iteration.

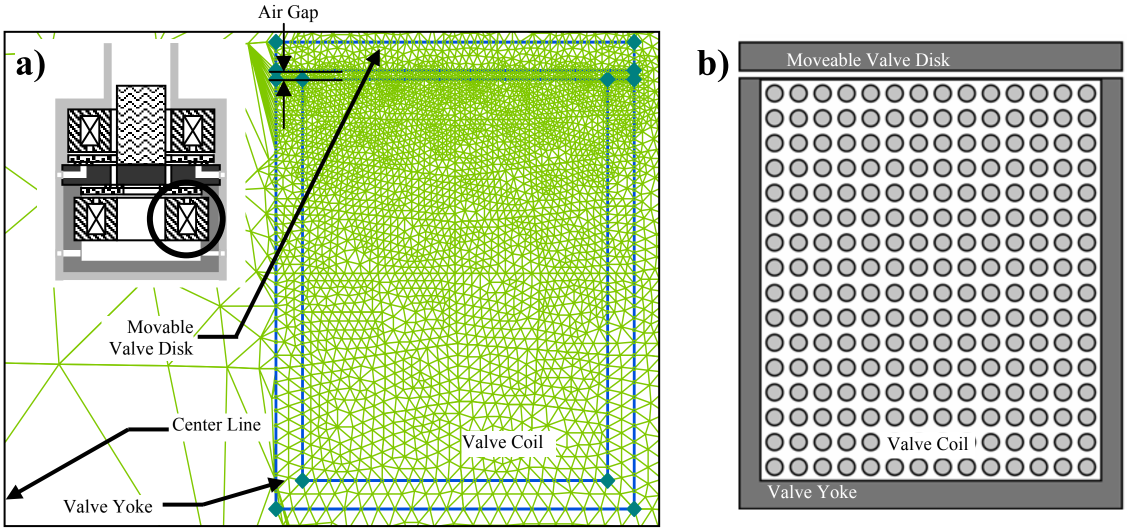


FIGURE 3. a) The baseline finite element valve design, located in the cold end as shown by the diagram in the upper right. b) A representative schematic showing key features of the baseline model. Finite element images given here are characteristic cross sections of a volume of rotation. The model boundary in all cases is a square 20.32 cm (8 in) in length impermeable to magnetic flux, which approximates infinite surroundings.

This process provides a substantial improvement over previous electromagnetic valve design methods for cryogenic applications based on simple analytical models [7, 8]. It allows the designer to explore the effects of many geometrical perturbations that are too small to accurately model with a less sophisticated method.

The baseline geometry is characterized by a cross-sectional area square in shape, representing an annular volume of rotation. The outer diameter is 4.57 cm (1.8 in), and the inner diameter is 2.44 cm (0.96 in). The thickness of the baseline valve yoke and valve disk is 0.076 cm (0.03 in).

In the evolutionary design process used here, several valve features were varied including the following: inner and outer diameter of the valve yoke, aspect ratio of the valve coil, axial cross-sectional area, thickness of the valve yoke base, valve disk thickness, valve coil corner fillets, and valve yoke air gap. This process resulted in the design shown in FIGURE 4. The finite element model predicts that at 100 amp-turns this valve design develops 21.886 N (4.93 lbf) on the valve disk when in its closed position. This quantity represents over 165 percent of the required opening force and a six-fold increase in performance over the baseline outlet valve model.

VALVE PERFORMANCE RESULTS

Valves were manufactured to meet the specified finite element dimensions as per the technical drawing in FIGURE 5. Experimental static testing of a valve's performance was conducted by loading the valve disk with a known hanging weight and energizing the valve coil to a current capable of holding that load.

The current was slowly reduced until the weight dropped, and the value of current at the drop was recorded. To determine performance of the valve in its closed position, a brass shim stock spacer of known thickness was placed between the valve yoke and the valve disk. This spacer approximated the air gap between the valve yoke and the valve disk in the cold end of the cryocooler.

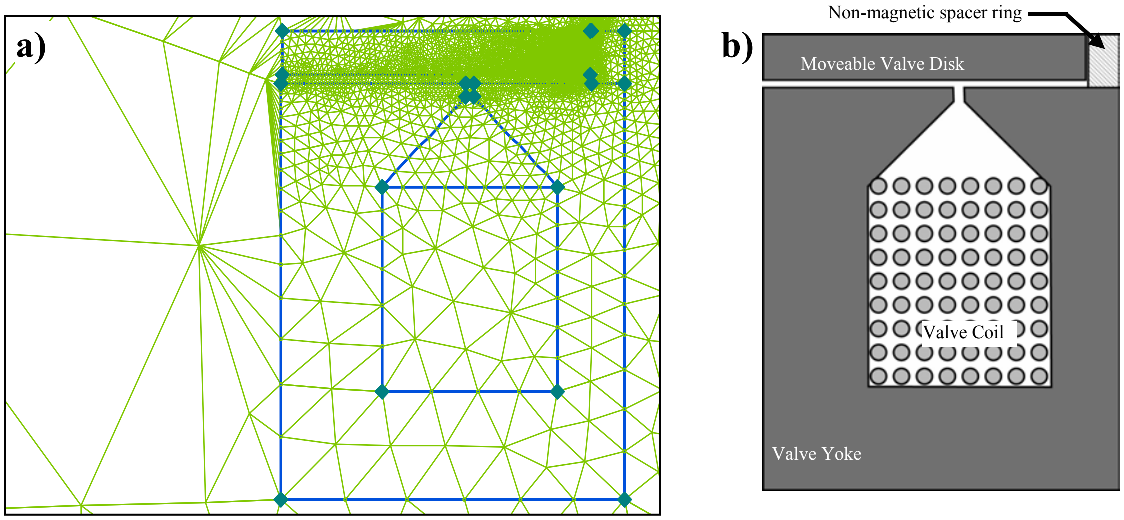


FIGURE 4. a) The final finite element design which demonstrates large performance improvements over the baseline, according to the finite element code. b) A representative schematic showing key features of the final model.

Upon testing, the real valve produced about 65 percent of the force predicted by the finite element model for an input of 110 amp-turns. The discrepancy can be attributed to geometric tolerances not incorporated into the model. The primary geometric tolerances contributing to performance degradation were interface surface roughness, component axial alignment, and shim gap tolerance. While difficult to model accurately using analytical methods, these features lend themselves to easy characterization with finite elements. Understanding how these factors influence the valve's performance allows for an educated design of a more efficient valve.

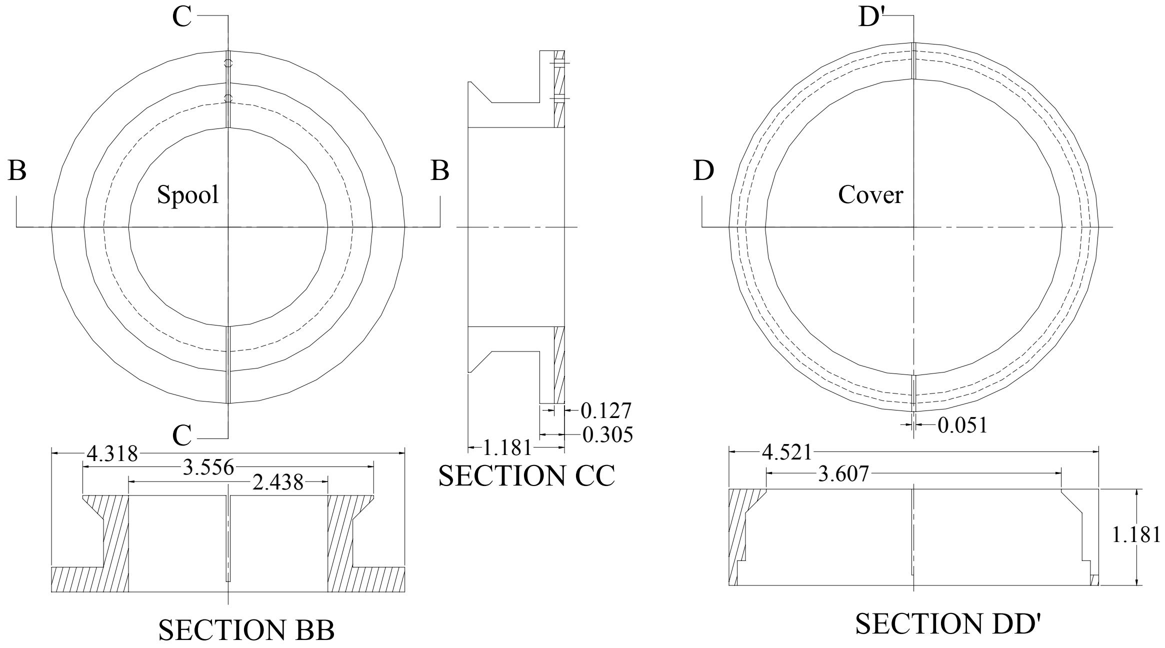


FIGURE 5. A technical drawing showing the two components of the valve yoke: the spool and the cover. The valve coil is wound onto the spool, and the cover is fit over the spool to create the valve yoke. All dimensions are in centimeters.

Interface Surface Roughness

The valves are assembled in two pieces: a spool is wound with wire and a cover is press fit over the spool to complete the valve yoke. Ideally, the interface of these two parts is characterized as perfectly smooth and uniform; the pieces join to create one continuous part. This situation represents the upper limit in magnetic performance for the interface.

In reality, the interface between the two metal surfaces is not smooth. The resulting interface creates additional resistance in the magnetic circuit, impeding the flux through the valve yoke. This resistance can be approximated by an equivalent air gap. As shown in FIGURE 6, the width of this gap can be adjusted to reflect the performance of the joint; the greater the width of the gap, the poorer the corresponding flux linkage through joint.

Gaps ranging from 0.0254 mm (0.001 inches) to 0.0762 mm (0.003 inches) in width were considered. Over the operational range of the valve, the difference in finite element performance between the ideal geometry and the geometry with the largest interface gap was about 2.5 N (0.56 lbf) at 50 amp-turns and almost 8 N (1.8 lbf) at 110 amp-turns.

Component Axial Alignment

When the cover and spool components are slid together, alignment of the magnetically active faces is important. The interference fit between the two parts makes it difficult to assure exact alignment, and there is uncertainty in the co-location of the parts. As shown in FIGURE 6, improper alignment increases the flux path length and reduces the contact area between the two pieces reducing the force the valve yoke can induce on the valve disk.

An axial offset tolerance ranging from 0.000 mm (0.000 inches) to +0.0762 mm (+0.003 inches) was explored. Over the operational range of the valve, the performance difference between the ideal geometry and the geometry with the largest axial offset was about 2 N (0.45 lbf) at 50 amp-turns and almost 6 N (1.35 lbf) at 110 amp-turns.

Shim Gap Tolerance

To facilitate static force tests, a 0.0254 cm (0.010 in) brass shim held the valve disk away from the valve yoke to approximate the air gap in the cold end, as shown in FIGURE 6. Imperfections on the component surfaces, folds in the shim's edges, and error in the instrument used to measure the shim create uncertainty in the accuracy of its thickness. These factors combine to obscure the distance between the disk and the active surface of the valve yoke by as much as ±0.0127 mm (±0.0005 inches).

Magnetic force on the valve disk is inversely proportional to the square of the distance between the valve disk and the active valve yoke surface. The ±5 percent tolerance in shim thickness results in a ±10 percent range of uncertainty in the theoretical force results.

When the cold end is assembled, the air gap between the valve disk and valve yoke may vary by much more than ±0.0127 mm (±0.0005 inches) because dimensional uncertainties in several aligned parts compound the error, and accurate measurement of the air gap difficult. Thus, this tolerance will be the primary geometrical factor degrading valve performance when the cryocooler is assembled.

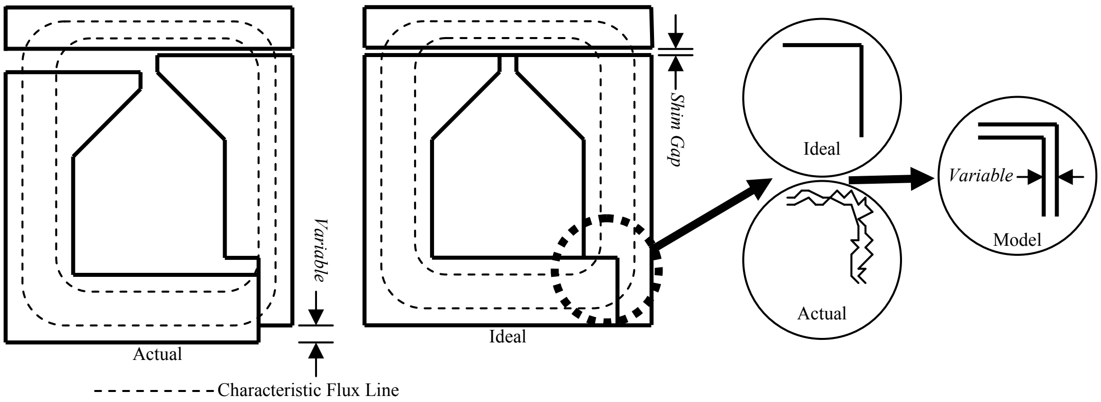


FIGURE 6. Three geometric tolerance uncertainties chiefly responsible for degraded valve performance: interface surface roughness, axial alignment, and shim gap tolerance.

Advanced Model for Performance Prediction

It is impossible to individually measure the contribution of each geometric tolerance uncertainty to the total degradation in valve performance. However, it is possible to define limits on valve performance by plugging the best- and worst-case tolerances values into the finite element routine.

These bounds, shown as broken lines in FIGURE 7 do capture the valve's measured performance. In comparison to the analytical model prediction, shown in FIGURE 7 as a solid line, the finite element approach provides a substantially more accurate prediction on the performance of electromagnetic valves for cryogenic applications.

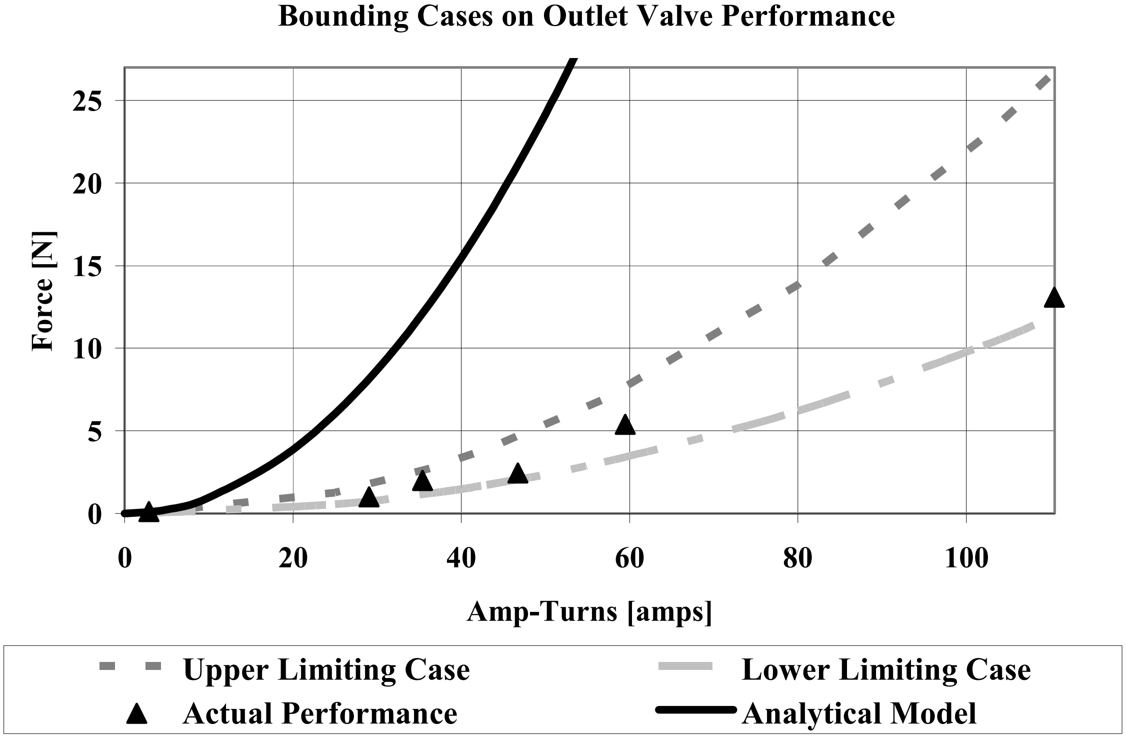


FIGURE 7. Bounding finite element performance curves compared against the analytical prediction offered by equation (1). The actual valve performance is captured within the predicted finite element bounds.

CONCLUSION

A design process for electromagnetic valves with cryogenic applications utilizing finite elements to predict performance has been developed. This process has been used to design and build electromagnetic smart valves to meet a predetermined performance specification.

For cryogenics applications, the benefits of electromagnetic valves include eliminating linkage heat leaks, reducing cold end mechanical complexity, and facilitating infinitely variable cycle control strategy. These features allow a user to tune the cryocooler for optimum performance in cool down and for temperatures other than the machine's temperature. Replacing mechanical timing with sophisticated electronic valve control equipment adds the benefits of reduced mechanical degradation, confidence in prolonged reliability, and facilitation of accelerated life cycle testing. With smart electronics that precisely control the residence time of the driving current in the valve coil, Joule heating in the cold end can be reduced to less than 0.0071 J/cycle.

Benefits must be traded against penalties incurred by electromagnetic valves: the loss of ability to mechanically un-stick jammed valve disks, a low limit on maximum valve opening force, and the need to precisely control valve disk striking velocity to preserve valve seat lifetime. Buildup of residual magnetic hysteresis on the valve yoke also needs to be overcome.

ACKNOWLEDGEMENTS

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