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Design, Construction, and Operation of a Two Cylinder Reciprocating Cold Compressor

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DESIGN, CONSTRUCTION, AND OPERATION OF A TWO CYLINDER RECIPROCATING COLD COMPRESSOR

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ABSTRACT

In an effort to operate Fermilab's Tevatron synchrotron at higher beam energies, plans exist to reduce the working temperature of the superconducting components. A proposed upgrade will utilize cold compressors as an addition to each satellite refrigerator, lowering the pressure of the 2-phase helium returning to the refrigerator system from the magnets. Coil temperatures as low as 3.9K are anticipated.

Since initial tests were performed with CCI reciprocating compressors and turbo compressors from Creare, Inc. and IHI Co., Ltd., the scope of the upgrade has broadened such that these machines no longer meet the pressure ratio, throughput, and efficiency requirements. Therefore new cold compressor development has been funded. In parallel with the purchase of a new centrifugal machine, Fermilab has developed a reciprocating unit capable of meeting the new performance criteria. The development history and operating characteristics of this machine are presented.

INTRODUCTION

Fermi National Accelerator Laboratory intends to upgrade its satellite cryogenic refrigeration system in order to permit an increase in Tevatron particle beam energy from the current 900 GeV maximum up to perhaps 1100 GeV. Elevated beam energies require stronger fields in the bending and focussing magnets that make up the synchrotron lattice. Stronger magnetic fields imply higher current in the superconducting windings. Finally, peak (or critical) current in a superconductor increases as the conductor temperature is lowered below the transition temperature. Tevatron magnets were designed such that the latent heat of flowing two-phase helium is used to transport heat out of the system. Hence magnet operating temperature is fixed by the pressure of the two-phase helium stream. The cryogenic system upgrade revolves around the installation of cold compressors to reduce the pressure of the two-phase circuit. It is planned to lower this pressure from the current 126 kPa (1.2 atm) to about 51 kPa (0.5 atm).

Several cold compressors have been tested in the pursuit of this upgrade[1,2]. It is required that the machines pump saturated vapor returning from the magnet strings with acceptable pressure ratio, throughput, and efficiency. Although a phase separator is to be installed upstream of the compressor, it is likely that some portion of the liquid fraction returning via the two-phase circuit will occasionally enter the compressor. For this reason,

* Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy

the machines must tolerate two-phase flow as well as saturated vapor. Finally, a high degree of reliability is crucial to the smooth, uninterrupted operation of the cryogenic system and the physics program it supports.

Details concerning the specification have evolved, requiring equipment development beyond that described in (1) and (2). Current requirements are listed in Table 1.

DESIGN DESCRIPTION

Single cylinder reciprocating cold compressors supplied to Fermilab by Cryogenic Consultants, Inc. (CCI) were of insufficient capacity to meet the newest specifications. Otherwise, performance was acceptable. Given the units' straightforward design and uncomplicated operation, it was decided that some sort of upgrade or modification to the existing machine was appropriate to reach desired capacity. Tests of the CCI compressors showed that throughput was about half the required level at the new design pressure ratio and intake conditions. This information was passed on to CCI where they suggested that the machine's volumetric displacement be doubled. This option implied large pistons, valves, and associated seal difficulties. Concurrent with these efforts, an alternative concept was generated at Fermilab. Given the success of the single cylinder unit, sketches were prepared showing installation of two CCI units in a common cryostat. The resulting idea described a two cylinder reciprocating compressor based on the CCI cold end/linear bearing assembly. Benefits included acceptable throughput as well as proven performance and smoother operation.

Fermilab has considerable experience with the Koch Process Systems, Inc. (KPS) expansion engine, utilizing this platform as the "wet" and "dry" expander in all satellite refrigerators. However, dry expander operation is not required for normal operation due to the introduction of LHe into the refrigerator return stream from the Central Helium Liquefier[3]. Because of increased CHL reliability and space limitations imposed by other elements of the upgrade, tentative plans include removal of all satellite dry expanders. Given this imposed surplus of rotating machinery, it was suggested that the new reciprocating cold compressor platform make use of the obsolete dry expander cryostats, topworks, and motor/controllers. Compressor construction would amount to scavenging all useful components from KPS expanders, the purchase of CCI cold end assemblies, fabrication of a few new pieces, and assembly. Table 2 outlines the parts list. For each cold compressor required, there is a corresponding dry expander slated for removal.

Table 1. Cold Compressor Specification

Normal Operation:	
Inlet condition	51 kPa sat. vap.
Outlet condition	126 kPa
Flow rate	60 g/s
Adiabatic efficiency (incl. static heat leak)	>60%
Off-Design Operation:	
Inlet range	41-81 kPa
Flow rate range	40-70 g/s
Minimum efficiency	60%
Standby (compressor off) Operation:	
Inlet condition	126 kPa sat. vap.
Flow rate	55 g/s
Pressure drop	<6.9 kPa
Upset Conditions:	
• 275 kPa, 100 ms pressure spikes during operation	
• Unit must reliably pump or otherwise protect itself from two-phase flow	

Table 2. Two Cylinder Reciprocating Cold Compressor Parts List

From CCI:

- (2) Cold gas pump cold end assembly with linear bearing assembly

From Existing KPS Expander:

- (1) 7.5 HP electric motor with controller
- (1) Flywheel
- (1) Flywheel frame
- (1) Crankshaft with associated bearing assemblies
- (1) Jackshaft with bearing assembly
- (1) Outer vacuum vessel assembly
- (1) Bayonet assembly (or FNAL equivalent)

Designed and Fabricated by FNAL:

- (1) Top plate
- (2) Housings for CCI cold end assemblies
- (2) Surge volumes for intake and exhaust, with associated piping
- (1) "Subatmospheric" bayonet assembly for intake bayonet
- (1) Frame riser
- (2) Connecting rod/clevis
- (2) Crank wheel
- (1) Motor mount with brackets

CONSTRUCTION DETAILS

The unit is pictured in Figs. 1 through 3. Specific elements of the design will be discussed in this section. Adaptation of the CCI elements was straightforward, requiring little work beyond accommodations for intake, exhaust, and warm end interfaces. The new cryostat top plate was machined to accept the CCI assemblies, as well as carry the flywheel, flywheel frame, and frame riser (required to allow for the increased height and stroke of the CCI assemblies relative to the KPS arrangement). While the motor/controller of an expander serves to extract work from the unit, a compressor consumes work. This switch was easily accommodated by the existing motor/controller package with a few electrical adjustments. The motor and instrument cluster were mounted on the frame riser to eliminate all connections to the cryostat. This simplifies maintenance by permitting unfettered removal of the top plate and attached cold end plumbing from the vacuum vessel. Warm end design is such that the cold end assemblies can be replaced by tilting back the flywheel and frame on the frame riser, a feature retained from the KPS design. New crank wheels and connecting rods were fabricated to mate the CCI piston shafts to the KPS flywheel. Finally, form-fitting aluminum covers with acrylic windows were fit to the flywheel, crank wheels/connecting rods, and jackshaft. The entire package was designed with the help of SDRC I-DEAS, a CAE program. This computer model was useful for overall component integration and as a visualization tool.

Cold end piping was designed similar to that of the CCI single cylinder design. Braided flex-hose was used where appropriate to limit stresses induced by thermal contraction. Appropriately sized intake and exhaust buffer volumes serve to minimize pressure oscillations induced by the unit. Instrumentation consists of intake and exhaust pressure taps connected to compound test gauges, intake and exhaust carbon resistor thermometers, and a helium vapor pressure thermometer on the intake stream connected to a compound test gauge. There is an independent resistor at the exhaust of each cylinder to facilitate separate cylinder efficiency measurements. Because of the contamination risks associated with compressor operation at subatmospheric intake conditions, special precautions were taken to eliminate non-metallic helium-to-atmosphere seals on the intake side.

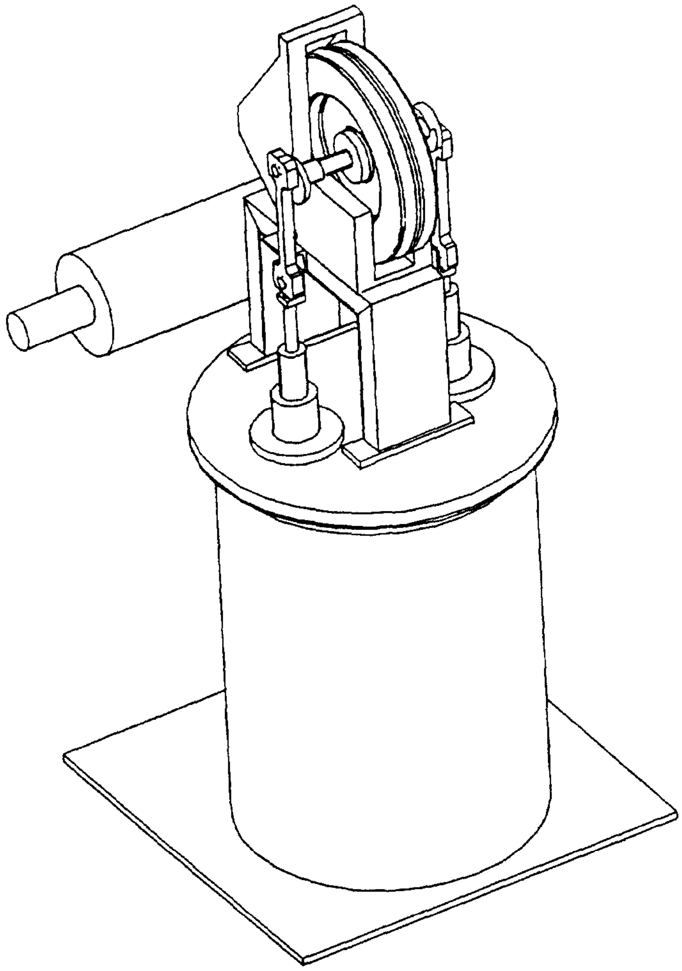

Fig. 1. I-DEAS Solid Model of the Prototype

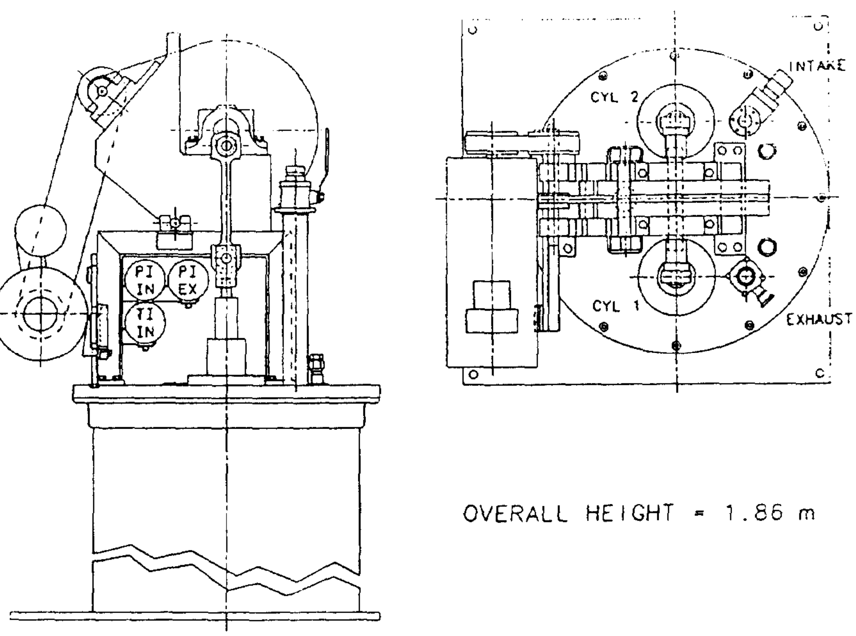

Fig. 2: Layout of the Prototype

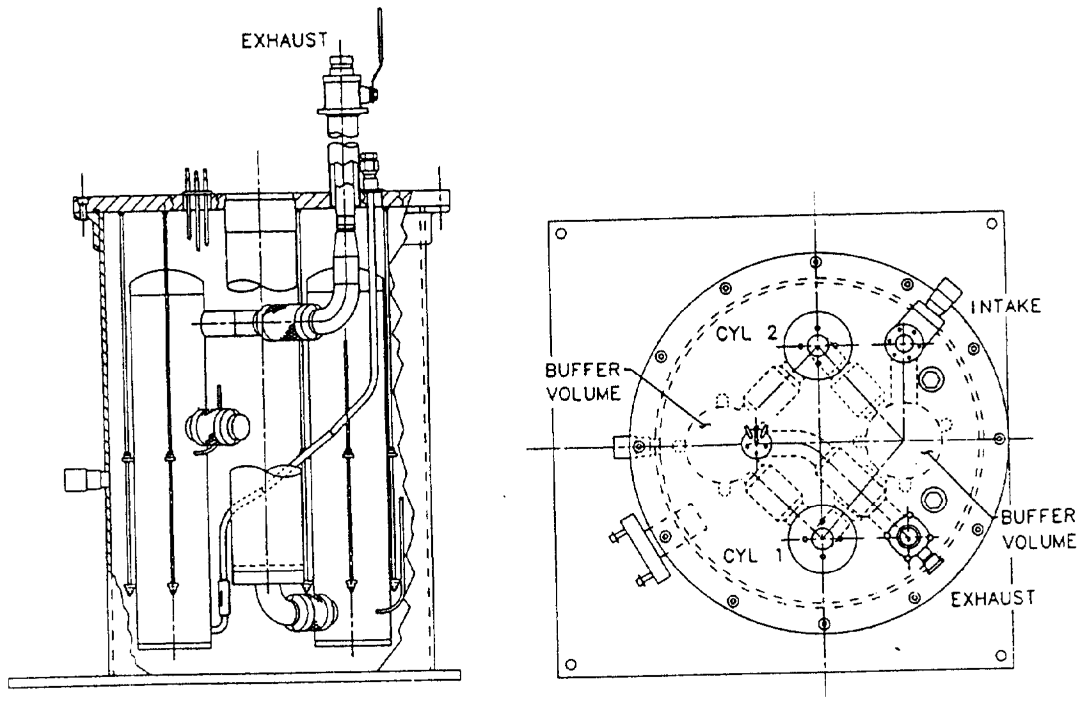

Fig. 3. Layout of the Internal Piping

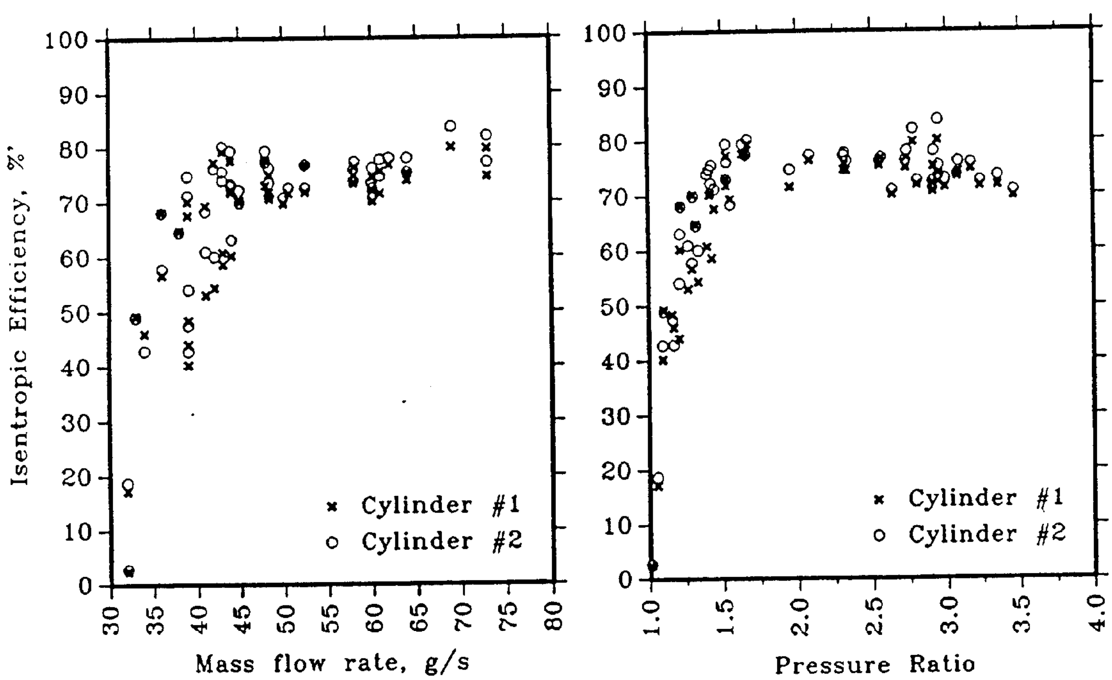

Fig. 4. Prototype Performance Data

As a consequence, gauges are welded or silver soldered directly to their sensing lines. The intake bayonet assembly is a special Fermilab design using copper gaskets instead of elastomer O-ring seals. Finally, rupture disks are used in favor of relief valves for overpressure protection. Given the inconvenience associated with the opening of a rupture disk, relief pressures are set well above the nominal system operating pressure.

PERFORMANCE

This prototype unit has performed as anticipated for over 500 hours of operation, both in a test refrigerator and in an actual Tevatron satellite. Efficiency is much the same as that of the original single cylinder CCI machines. As one would expect, throughput is double the CCI units. In Tevatron service, the prototype was more than capable of meeting the compressor specification. Flywheel speeds never exceeded 300 rpm, in part due to the limitations of the motor/controller and a somewhat inappropriate pulley ratio. CCI single cylinder units have operated at 400 rpm for extended lengths of time with acceptable performance; it is reasonable to expect the two cylinder prototype, with its improved balance, to meet or exceed this speed without difficulty. Therefore the prototype is most likely capable of well exceeding the specification with regard to throughput and pressure ratio. Fig. 4 shows performance data, taken independently for each cylinder. Maintenance requirements are proving to be a cross between those of our CCI compressors and our KPS expanders. Warm end maintenance is performed identically to our expander schedule, while cold end behavior is no different from our existing CCI machines.

CONCLUSIONS

A successful two cylinder reciprocating cold compressor was fabricated by combining two CCI compressor cold end assemblies with elements of a KPS dry expander. Performance is essentially identical to that of two CCI single cylinder compressors arranged in parallel, except for reduced static heat leak. The KPS platform is well suited to this modification, with appropriately sized cryostat and flywheel. In addition to meeting the FNAL cold compressor specification, the prototype is well understood by FNAL maintenance technicians due to their experience with KPS expanders and the straightforward design of the CCI assemblies.

ACKNOWLEDGEMENTS

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