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Experience with Small Turbomachinery in a 400 Watt Refrigerator

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EXPERIENCE WITH SMALL TURBOMACHINERY IN A 400 WATT REFRIGERATOR

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ABSTRACT

A refrigerator similar to one of the Fermilab Tevatron satellites was re-configured to use turbomachinery instead of the reciprocating equipment typical of the installations. A Sulzer dry turboexpander, Creare wet turboexpander, and IHI centrifugal cold compressor have been installed and operated for about 8000 hours. Experience was gained both with the rotating machinery and with the refrigerator itself as it interfaced with the load. Equipment was set up to regulate in the same manner as the reciprocating devices had. Heat loads and operating mode were adjusted and evaluations made regarding the behavior of the devices.

Individual equipment performance is described, as well as system behavior and overall integration of the machinery. In particular, attention is paid to the Creare wet turboexpander. This device is operated for the first time as part of a full scale refrigeration system, testing not only its performance at the design point but also its off design characteristics and behavior in transient situations.

INTRODUCTION

Fermilab's Accelerator Division/Cryogenics Department is responsible for the maintenance and operation of both the Central Helium Liquefier (CHL) and the system of 24 satellite refrigerators which provide 4.5K refrigeration to the magnets of the Tevatron synchrotron.[1] The satellite refrigeration group also operates several additional helium refrigerators which are generally tied to the Tevatron system but may not be directly involved with operation of the accelerator. One of these systems is located at the antiproton source. This refrigerator (known as PR) is essentially identical to the Tevatron satellites and originally supplied LHe to some electronics associated with antiproton production. Advances in electronics eliminated the need for 4.5K operation which allowed the Division to make the PR refrigerator available to the Cryogenics Department for use as a test bed. In the last few years PR has been used for a variety of tests including operator training and various small experiments. Most recently, PR has been home to several pieces of high speed turbomachinery. This equipment has operated for the past year providing data both on individual component performance and on system behavior. Figure 1 is a photograph of the PR refrigerator.

The rotating expansion engines used in the Tevatron satellites are reciprocating devices manufactured by Process Systems. Inc.[2] These expanders achieve mid - 70% efficiency and

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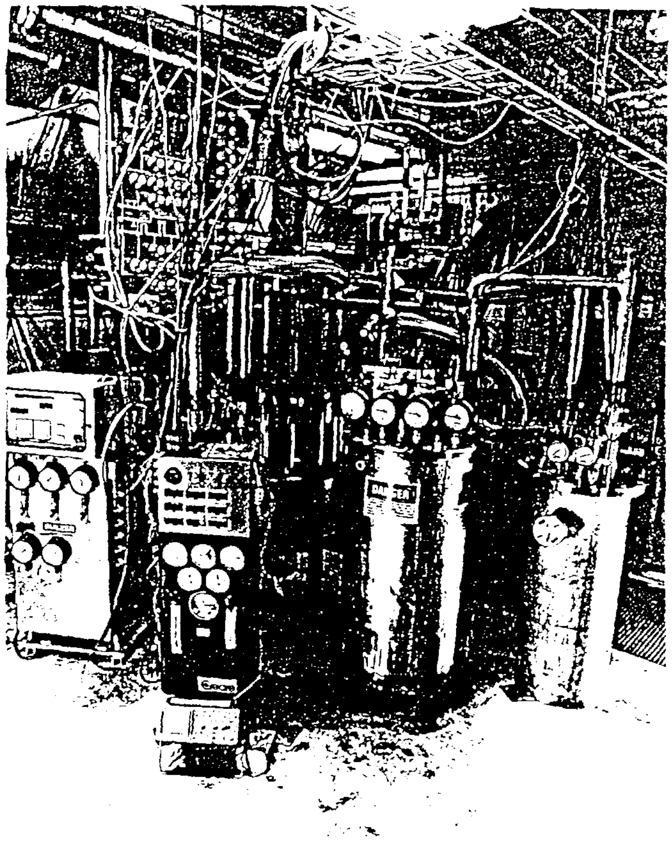

Figure 1: Photo of PR refrigerator building showing (l-r) Sulzer dry expander, Creare wet expander, 160L dewar, and IHI cold compressor. The valve box and horizontal heat exchanger are visible in the background.

are well integrated with our existing system. However, they possess drawbacks which make them undesirable in certain other applications. These drawbacks include physical size, maintenance requirements, and flow pulsation created by the positive displacement nature of the units. The Cryogenics Department is interested in gaining experience with high speed rotating machinery, in part to advance the state of the art but also to provide a working system where experiments may be conducted free of flow pulsation. There is considerable experience at the CHL with larger scale turbomachinery; the unique aspect of PR is the use of small devices in a 50 g/s, 400+ watt refrigerator. This paper describes the system layout, the details of the turbomachinery, and the performance both of individual components and of the overall refrigerator in various operational and upset modes.

SYSTEM DESCRIPTION

The PR refrigerator was built to supply LHe to three dewars housing electronics associated with the antiproton source. The plant is based on the Tevatron satellite refrigerators, using the same heat exchanger and (originally) reciprocating expanders. Following an electronics upgrade which obviated the need for LHe cooling, the refrigerator was idled or used for training or experimentation. In early 1994 the reciprocating expanders were replaced with high speed turbomachines which had formerly been in storage. Our prototype centrifugal cold compressor as well as a 160L dewar were added to create a complete refrigerator. A 1000W heater in the dewar provides the heat load. Figure 2 shows a simplified schematic of the system.

The Tevatron high pressure header supplies about 75 g/s of 2 MPa, ambient temperature helium to the tube side of the heat exchanger. Part of the supply is precooled in a LN_2/GHe exchanger before joining the main stream. The gas is then cooled in counterflow with the low pressure (0.13 MPa) return to about 6K at the cold end. The dry expander is

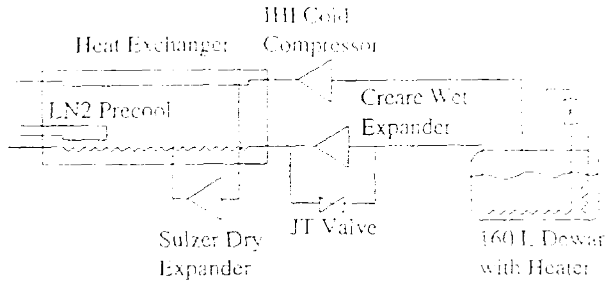

Figure 2. Simplified schematic of the PR refrigerator showing location of turbomachinery

located at the 20K point in the exchanger train and takes a (design) flow of 30 g/s, discharging into the shell side. Tube side pressure drop with these flow rates is about 0.3 MPa, giving a 45 g/s, 6K, 1.7 MPa wet expander inlet. This pressure is less than design for the wet expander and may partially explain the reduced efficiency measured on that unit. The wet expander exhausts at pressures at or below 0.3 MPa depending on how the system is configured. Flow passes through a finned tube coil where it is subcooled by the liquid in the 160L dewar before being throttled into the dewar itself. A heater in the dewar maintains liquid level. The cold compressor regulates dewar pressure by drawing vapor from the dewar and discharging to the shell side of the heat exchanger. Cold compressor inlet pressure ranges from 140 kPa (compressor off) to about 50 kPa with the compressor operating at design.

ROTATING EQUIPMENT

Sulzer Dry Expander

The standard reciprocating dry (20K) expander is replaced with a Sulzer turboexpander consisting of two TGL 16 turbines in series. The units are housed in a common free standing cryostat with all required instrumentation and controls on board, including speed pickups for both shafts. Dynamic (self-acting) gas bearings are used which require no external gas supply. Flow rate is controlled by an electric actuated inlet valve which is controlled via the Fermilab distributed control system. Valves on the turbine brake circuits are used to set shaft speeds. They are manually positioned and require adjustment for optimum efficiency at given inlet conditions. Care must be taken to avoid overspeeding the turbines on startup, either by improper brake valve position or excessive gas flow. The turbines are protected by overtemperature and overspeed interlocks to limit the risk of damage. The brakes are water cooled although we have added supplemental fins and fans to reduce operating temperature.

This expander has been at Fermilab since the mid-1980's and has been installed at various locations within the Division, including (for awhile) a Tevatron satellite refrigerator. At that time the unit was not configured for remote control of the inlet valve so operations were cumbersome, requiring visits to the refrigerator to adjust flow rate and turbine speed. In the current installation at PR, the unit automatically regulates flow rate based on discharge temperature. Brake circuits are still tuned by hand but this has proven acceptable as most brake adjustment occurs during startup and cooldown - once the unit is cold, the turbine speeds are not strongly affected by small changes in inlet valve position as the expander regulates. Table 1 lists dry expander parameters and operating data.

IHI Cold Compressor

The cold compressor at PR is the same unit described in an earlier paper.[3] It is manufactured by IHI Co., Ltd. and served as our prototype for units eventually purchased in support of the Tevatron low temperature/higher energy upgrade.[4] It consists of a single stage impeller and shaft supported by dynamic foil gas bearings and powered by a water cooled variable frequency induction motor. Table 2 shows selected parameters for the compressor. Performance data is given in the above reference.

Table 1. Sulzer Dry Turboexpander

Turbine Type:	T1: TGL 16-11/B22	design speed 4.7 kHz	
	T2: TGL 16-14/A28	design speed 4.4 kHz	
	Fluid: pure helium		
	Flow: 30 g/s		
	Inlet: 1.82 MPa, 25K		
	Outlet Pressure: 0.122 MPa		
Measured Performance:	Inlet:	1.58 MPa, 24.32K	
	Exhaust:	0.15 MPa, 14.77K	
	Flow Rate:	31.6 g/s	
	Speeds:	T1: 4.35 kHz, T2: 4.10 kHz	
	Efficiency:	60.8% isentropic	

Note: efficiency is measured from upstream of the inlet valve to downstream of turbine 2. Inlet valve ΔP is 0.16 MPa, giving a turbine inlet condition of 1.42 MPa, 24.24K and actual turbine isentropic efficiency of 62.6%.

Creare Wet Expander

Creare Inc. developed a miniature wet turboexpander in the late 1980's which was tested at Fermilab[5]. This research was funded by the U.S. Department of Energy, which took possession of the expander at the conclusion of the project. In turn, Fermilab requested and was granted ownership of the device on behalf of the DOE. Expander performance during the initial tests is reported in the above reference. The unit at that time was essentially a laboratory device which required continuous supervision during operation. This was acceptable for initial operation and proof of concept but further controls and interface work were required to allow "hands free" operation in an industrial setting.

Most important for unattended operation was a means of automating a balancing circuit which maintains equal pressure on either side of the shaft seal. The expander is designed with a labyrinth seal at the lower end of the shaft between the lower journal bearing and the turbine. This seal is exposed to system pressure on one side and is ported to a regulated supply of warm helium on the other side. Since pressure at the system side of the seal varies depending on inlet conditions, the pressure at the other side must be adjusted to maintain zero differential pressure across the seal. Leakage from the process side up into the expander risks freezing out the bearings while leakage in the other direction adds warm gas to the process stream and destroys efficiency. During initial expander testing the labyrinth seal was balanced by observing a differential pressure gauge and manually adjusting a regulator. This action was necessary every few minutes in order to maintain pressure differentials less than ± 2.5 kPa. Automatic operation of this labyrinth balancing circuit has been accomplished by motorizing the regulator and driving it with a signal from a differential pressure transducer. A Dwyer Capsu-Photohelic gauge with a center zero, ± 3.7 kPa range, and adjustable limit switches on both the positive and negative side is wired to a Hurst stepper motor attached through a telescoping linkage to the regulator. Control is

Table 2. IHI Cold Compressor

	Design	Off Design	Standby
Inlet Pressure:	51 kPa	41-81 kPa	142 kPa
Inlet Temperature:	sat. vap.	sat. vap.	sat. vap.
Outlet Pressure:	142 kPa	142 kPa	
Flow Rate:	60 g/s	40-70 g/s	55 g/s
Speed:	1.3 kHz	1.5 kHz max.	0 Hz
Input Power:	1.25 kW	1.5 kW max.	

Table 3. Creare Wet Turboexpander

	Design	Measured
Flow Rate:	50 g/s	43 g/s
Inlet:	1.9 MPa, 6K	1.8 MPa, 6K
Outlet Pressure:	0.22 MPa	0.25 MPa
Pressure Ratio:	8.6	7.2
Speed:	6.4 kHz	5.9 kHz
Isentropic Efficiency:	72.2%	60 ± 10 %*

*calculated across expander and inlet valve with valve at 100% (zero ΔP); does not include effect of 0.8 g/s warm helium flow for bearings, brake, and labyrinth circuit

a simple on/off circuit which drives the stepper motor in the desired direction when the differential pressure across the labyrinth seal exceeds the position of one of the limit switches. Motor step angle is 0.1 degree, with an adjustable frequency of between 5 and 480 Hz. This simple, self contained system has proven sufficiently versatile to provide accurate control of seal differential pressure to within ± 1.5 kPa without serious overshoot during normal operation. A more sophisticated control scheme may be implemented in the future which makes use of the Tevatron distributed control system, giving the labyrinth balancing circuit all the capabilities of a standard refrigerator control loop.

Wet expander speed is variable up to 7 kHz, with a design speed of 6.5 kHz. Shaft speed depends on inlet conditions and the pressure in the brake circuit. The brake consists of a pressurized, water cooled, closed loop helium circuit driven by an impeller attached to the top end of the expander shaft. Brake circuit pressure is controlled with a regulated supply of warm helium to optimize speed for maximum efficiency and to prevent overspeeding when the expander is warm. Shaft speed is sensed with a capacitance probe and displayed on an oscilloscope. Currently the brake pressure is manually adjusted

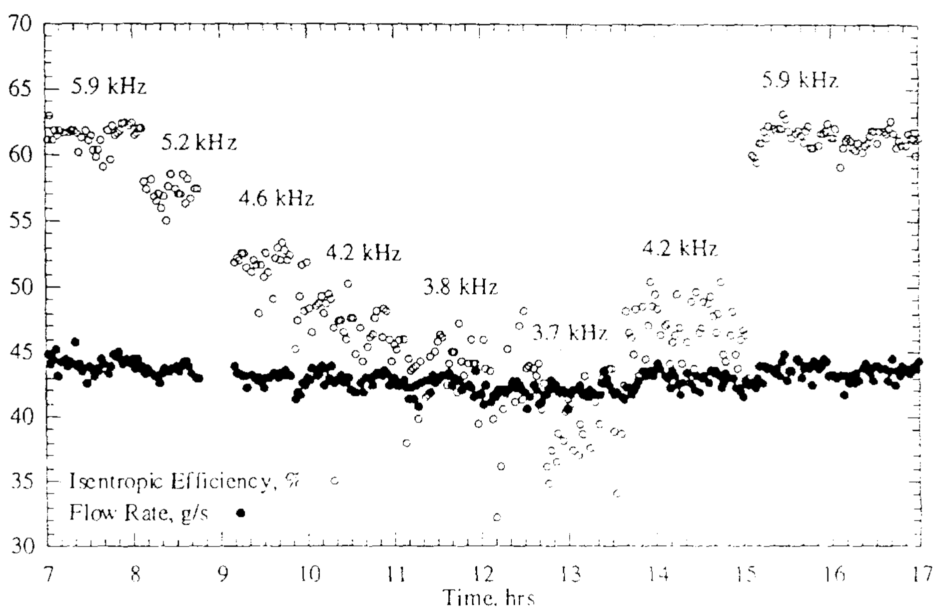

Figure 3. Creare wet turboexpander efficiency and flow rate over a ten hour period. The inlet throttle valve is wide open. Inlet and exhaust pressures are a constant 1.8 and 0.26 MPa. Inlet temperature varies from 5.5 to 6.5K. Frequency numbers correspond to turbine speed as brake pressure is varied between the 0.45 MPa minimum (producing a maximum speed of 5.9 kHz - less than the design of 6.4 kHz) and 1.3 MPa, the highest safe pressure given the thrust bearing instability. Note mass flow is under the 50 g/s design point, perhaps due to reduced inlet pressure caused by high pressure drop in the heat exchanger.

although future plans call for automatic adjustment based on expander speed. For the most part the brake circuit runs at its minimum pressure of 0.45 MPa so adjustments are infrequent. The exception is during cooldown when higher brake pressure must be maintained to prevent shaft overspeed. Maximum brake pressure is rated equal to the supply for the expander's pressurized (static) gas bearings (about 2 MPa) although we have been limited to 1.3 MPa due to a thrust bearing instability which causes severe, audible shaft vibration at certain ratios of bearing supply to brake supply pressure. Wet turboexpander parameters and performance are listed in Table 3 and Figure 3.

SYSTEM PERFORMANCE

Capacities

Liquefaction and refrigeration capacities were measured directly using the 160L dewar and built in 1 kW heater. Both quantities were measured with and without the wet turboexpander, substituting an adiabatic throttle valve. Table 4 lists maximum capacities achieved at PR after experimenting with various tunes. Refrigeration at LHe temperature is given directly by heater power required to maintain a stable liquid level while liquefaction rate is measured by the rate of liquid accumulation in the dewar with the heater off. Refrigeration results are in reasonable agreement with Tevatron satellite refrigerator performance in "stand-alone" mode (no LHe injection from the CHL). This is expected since PR is essentially identical to a Tevatron satellite except for the rotating machinery and the load. Liquefier capacity is about 70% of a satellite in stand-alone mode with wet expander and 40% of a satellite in stand-alone/JT operation.

Controllability

A key element of the PR turbomachinery test is to document the behavior of these small units as they interact with the cold box and each other over changes in flow, heat load, and tune. Efforts have been made to provide each unit with regulating capability, allowing it to adjust flow rates and speeds as conditions warrant. The IHI cold compressor adjusts speed based on its inlet pressure, effectively controlling the temperature of the liquid in the dewar.

Tevatron satellites use the speed of the reciprocating wet expander to control expander exhaust pressure, thereby fixing the pressure in the "single phase" circuit of the Tevatron magnet strings. The analogy at PR is to allow the Creare wet turboexpander inlet valve to throttle the expander flow based on exhaust pressure. This works quite well from a control standpoint given an appropriate valve/actuator combination. However, overall efficiency of the expander package suffers since some portion of the expansion is performed across a valve with 0% efficiency. With the inlet valve at 62% open, the expander inlet pressure is reduced from 1.8 MPa to 1.3 MPa. Although efficiency across the expander itself is maintained at 55%, the overall efficiency of the unit (valve plus expander) is measured to be about 30%.

The Sulzer dry expander operates out of a more loosely coupled control loop than the other two machines. This expander, like the Creare, adjusts flow rate with a throttle valve upstream of the turbines. The control point is the dry expander exhaust temperature as measured by a hydrogen vapor pressure thermometer (VPT). By careful selection of control loop parameters, this system was made to control to within ± 34 kPa on the VPT - a temperature resolution of a few degrees. This is a satisfying result given the limited useful range of the VPT and the steepness of the pressure vs. temperature curve for that device. Of course the Sulzer expander suffers the same efficiency penalty as the Creare imposed by inlet throttle valve positions less than 100%.

Table 4. PR Refrigerator Capacities

	Wet Expander Mode	JT Valve Mode
Liquefaction	84 L/hr	22 L/hr
Refrigeration	575W	310W

Transients & Upsets

There have been ten interruptions in PR operation in the last 16 months, three of which were caused by site-wide power outages at Fermilab. The other stoppages were intentional for equipment maintenance or modification. Each interruption involved a shutdown of all three turbomachines and subsequent restart. This has provided experience with warmup and cooldown of these units. In addition, the safety interlocks were tested during the power outages. In particular, the Creare wet expander is vulnerable in a power outage because it requires a pressurized helium supply for the bearings, brake, and labyrinth balancing circuit. The inlet valve is fitted with a fail closed actuator which shuts off flow to the expander. A bearing gas accumulator provides sufficient ballast to allow the shaft to spin down before the helium bearing supply pressure dwindles (warm gas for bearings, etc. is taken from the Tevatron high pressure header; a power outage shuts down our compressors causing this header to depressurize.) The Sulzer dry expander and IHI cold compressor use self-acting gas bearings which are pressurized by the process stream and as such are not at risk during an outage.

The wet expander survived the first two power outages with no perceived ill effects. In both cases, the unit was successfully restarted after resumption of power and performance was equal to that before the outage. However, the unit failed to spin up after the third outage which occurred on 22 June 1995. A loud vibration typical of the thrust bearing instability was heard as we re-pressurized the brake circuit in preparation for opening the inlet valve. During this vibration, the speed trace on the oscilloscope went flat, suggesting seizure of the shaft. There has been no shaft motion since. The wet turboexpander operated for about 7500 hours with no maintenance prior to this failure.

CONCLUSIONS

The PR refrigerator at Fermilab has operated for over a year using high speed turbomachinery instead of the standard reciprocating hardware found in a Tevatron satellite refrigerator. Although efficiencies are less than those measured on reciprocating devices, the units have met the modulation requirements of a satellite. In addition, they are low (or no) maintenance devices which are (or could be) significantly more compact than their reciprocating counterparts. This is important where space constraints, remote location, or accessibility problems outweigh the need for maximum efficiency. Finally, the continuous flow nature of these devices eliminates the flow pulsations and noise inherent in a positive displacement reciprocating machine.

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