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OPERATIONAL TESTS OF THE BNL 24.8 kW, 3.8 K HELIUM

REFRIGERATOR*

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ABSTRACT

The BNL 24.8 kW refrigeration system is completely installed and major portions of the acceptance tests have been completed. So far, the equipment tested has performed at or above design levels. The room temperature helium compressor station has been completely tested and accepted. The two-stage oil injected screw compressor system exhibited an isothermal efficiency of 57% while delivering a helium flow in excess of 4400 g/s. Data on the performance of the make-up gas cryogenic purifier is given.

The refrigerator turbomachinery, 13 expanders and three cold compressors, has been tested at room temperature for mechanical integrity and control stability. The first cooldown to operating temperature will be attempted in late August, 1985.

MASTER

INTRODUCTION

Detailed design of the cold box section of a refrigerator to produce the equivalent of 24.8 kW of helium temperature refrigeration and liquefaction was begun in 1980. The cycle, which has been reported earlier,¹ does not use liquid nitrogen precooling and was designed to reach temperatures as low as 2.5 K utilizing a two-stage centrifugal compressor system to pump saturated helium vapor from liquid baths in the cold box. In 1982, a separate contract for the compressor station was initiated.

The contracts were for what is essentially a turn-key system which was provided by Koch Process Systems, Inc. (KPS), with the exception of the process control computer system provided by Brookhaven National Laboratory (BNL). The equipment was fabricated and installed. Component testing began in December, 1984, when the first compressor was started. Testing of subsystems continued until compressor acceptance tests of the total system were initiated and completed in April, 1985. Tests of the turbomachinery in the cold box began in July, 1985. It is expected that the plant will be cooled to operating temperature for the

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first time in late August. Completion of the acceptance tests is expected in October, 1985.

Future plans for the refrigerator call for its use in tests of a 1 km long string of SSC magnets and, eventually, to provide refrigeration for a proposed accelerator, the Relativistic Heavy Ion Collider (RHIC), in the tunnel originally built for CBA.

TEST RESULTS

Main Compressors

A block diagram of the major equipment in the compressor system is shown in Figure 1. The specification for the system required that full flow be maintained when one compressor of either stage was inoperative. Twenty first stage and five second stage compressors have been installed. It was expected that the specified flow and efficiency would be met with 19 and 5, respectively, compressors in operation. The test showed that only 18 and 5 were required, so that there are actually two redundant first stage compressors. The required flow can be maintained with four second stage compressors (at lower efficiency), so one is redundant.

Data from measurements taken during the compressor acceptance test are shown in Table 1. This shows a power consumption rate of 13.542 MW for a helium flow of slightly over 4400 g/s. The calculated isothermal efficiency is 57%. The power for oil pumps and parasitic pressure drop losses in piping and coolers are included in this value. The calculated efficiencies for each stage at this operating point are also shown.

The compressors (both first and second stage) are oil-injected screw compressors and were built by Howden, Inc. They have 321 mm diameter rotors, L/D ratio of 1.65 and built-in volume ratio of 2.6.

The compressors were fabricated to special close tolerances and reduced clearances. The oil-injection ports were also designed to optimize the oil flows for this application. These design modifications increased the predicted isothermal efficiency by several points relative to standard refrigeration compressors.

The skid design, piping design and fabrication was done at KPS. As shown in Figure 2, the compressors are mounted above the oil sumps on these skids. The two compressors on each first-stage skid share a common oil supply and bulk oil separation system. The second-stage compressors are mounted one per skid.

Table 1. Compressor Acceptance Test Data

Parameter	Overall Process	First Stage	Second Stage
Flowrate (g/s)	4403	4403	4403
Temperature (K)	308.8	308.8	308.8
Pressure In (kPa)	108	108	398
Pressure Out (kPa)	1670	398	1670
Power Input (MW)	13.542	6.715	6.825
Isothermal Efficiency (%)	57.0	54.8	59.3

COMPRESSOR SYSTEM BLOCK DIAGRAM

Figure 1.

Figure 2. Elevation views of First Stage Compressor Skid.

Two second stage compressors were operated in parallel as single-stage compressors to obtain the results shown in Figure 3. This curve shows clearly the peak in efficiency at the design (in the intended two-stage operation) pressure ratio of about 4 to 4.5. The absolute value of the efficiency is several points lower than could be obtained with a compressor optimized for these test conditions. The measured efficiency is low because (1) the quantity of oil injected is higher than necessary for the conditions of operation and (2) the electric motor is operating at only 25% to 50% of its nominal level which is a less efficient operating point. The first stage compressors have an efficiency of about 54% when operated with a pressure ratio of 4. This is shown in the upper curve of Figure 3. First stage compressors were not used at higher pressure ratios because the electric motors are too small to meet the compressors' power requirements at the high pressure ratios. For a compressor optimized at each point, the entire second stage curve could probably be shifted upward to match the first stage in efficiency at 110 kPa suction pressure. The measured efficiency of the second stage when operated with 398 kPa suction pressure (see Table 1) was 59.3%. All results are for compressors with their slide valves in the fully loaded position.

Oil Removal

Bulk separators are located at the discharge of each compressor. A combination of gravity separation, demister pads, and coalescing filters reduce oil content in the helium gas to less than 200 ppm. Four stages of coalescing filters, in series, remove entrained oil droplets from the helium stream exiting the aftercoolers. Oil vapor that may remain in the helium stream is subsequently removed by a charcoal adsorber bed following the final coalescing filter. The clean high pressure helium stream leaving the charcoal bed then passes through final particulate filters and proceeds to the cold box.

Laser aerosol particle detectors are located between the third and fourth stage of coalescing filters and following the final particulate filter. These detectors continuously monitor the helium gas for the presence of aerosols down into the sub-micron size range. Measurements taken during the acceptance tests indicate that the oil content of the gas does not exceed 0.5 ppb by weight, the lower limit of detection with the PPM (Knoxville, TN) detector used.

Utility Compressor

The utility compressor is used intermittently in this system to compress gas for recovery (see Fig. 1) and to provide relatively small gas flows for purposes of purging and circulating for system clean-up. This oil-injected screw compressor is a Howden WLVH-255, L/D ratio of 1.10 and a built-in volume ratio of 5.0. Its nominal throughput is 73.5 g/s with suction at 1.05 atm. This compressor was operated through a range of pressure ratios during the test. The efficiency measured at various points is shown in graphic form in Figure 4. Note the similarity to the curve in Figure 3. The efficiency peaks at a higher pressure ratio as expected due to the higher built-in volume ratio.

Cryogenic Purifier

A cryogenic purifier is used to purify make-up gas (see Figure 1) and for circulation to clean-up the load. The purifier is a dual unit designed for continuous purification of 250 g/s of helium. Design impurity levels are up to 50 ppm of nitrogen, 30 ppm of water vapor and 1 ppm of compressor oil. Total impurities in the exit gas are required to be less than 1 ppm.

A performance test was conducted and it established that this unit had a pressure drop (clean heat exchangers) of 50 kPa and met the LN₂ consumption specification of 42 mL/s. No calibrated impurity source was available to test the purification ability of this unit, but it has been operated at varying inlet impurities with acceptable performance.

Cold Box

The first cooldown attempt for the system is scheduled for late August, 1985. All turbomachinery was supplied by Rotoflow Inc., and has oil-lubricated bearings. Seven expanders are used in steady-state operation and six additional expanders provide redundancy as well as additional capacity during cooldown. A two-stage compressor is used to pump saturated helium vapor to pressures of 0.1 atm in the designed cycle. Another compressor is used as a high-flow, low-head circulator through the load.

All of this turbomachinery has been operated at room temperature demonstrating that the equipment is sound mechanically. Temperatures to

EFFICIENCY CURVE **OIL-INJECTED HELIUM SCREW COMPRESSOR**

HOWDEN MODEL WLVH-321/16526
 ROTOR DIA. = 321 mm, L/D = 1.65, VOL. RATIO = 2.6

Figure 3. Main Compressor Efficiency Curves.

EFFICIENCY CURVE **OIL-INJECTED HELIUM SCREW COMPRESSOR**

HOWDEN MODEL WLVH-255/1150
 ROTOR DIA. = 255 mm, L/D = 1.1, VOL. RATIO = 5.0

Figure 4. Utility Compressor Efficiency Curve.

about 185K were incidentally produced during the turbine tests. In this plant, helium flows through as many as four expanders in series. Each expander has variable area inlet vanes. Various control philosophies (turbine speed, interstage pressure, etc.) were tried to obtain most stable operation. A few changes in the oil system for the turbines were indicated by the tests and will be made before the first cooldown.

Control System

Control of the system is by means of a process control computer system which also provides data logging and analysis functions. This system was purchased from ANATEC, Inc. with software applications programmed by BNL personnel.

The control system is hierarchical in design, consisting of a DEC 11/44 host and redundant 11/34 processors communicating via a 1 megabaud data highway. The 11/34's interface compressor and refrigerator I/O hardware and contain real time data tables and all logic for process monitoring and control. An image of the 11/34 data tables is written into the 11/44 processor over the data highway which permits the operator work station color consoles access to the system through either CPU. Normally one 11/34 is on line performing all logic and control loop calculations while the 11/44 handles alarming and the more time consuming calculations which use the NBS helium thermophysical properties program, such as cold helium flowrate, system efficiency and refrigerator capacity.

Input/output hardware services about 1600 points scanned every 0.1 seconds. Most of the channels are standard process interfaces of the 4 to 20 ma, 115 Vac and 0 to 5 Vdc variety. Cryogenic temperature sensor data acquisition demands² are unique however, and must be preprocessed to gain the necessary accuracy and to unload the control system computer from the high volume of floating point calculations. An 8086/8087 microprocessor system performs linearization of all platinum, silicon diode, germanium and cryogenic thermistors, converts to engineering units and places the output data in RAM locations. These RAM addresses are declared by tag name as physical I/O of the process computer and temperature data is read and automatically placed in internal floating point temperature tables.

Logic and control is programmed in the CRISP language which has access and can write to the data tables. It is extremely efficient for batch and closed loop control, consuming less than 30 kilowords of memory for all compressor and refrigerator applications programs.

The color CRT's are serviced by a separate program which links live data base variables to the screen. Variables on the screen may be protected from operator interaction or in the case where the operator is permitted to make adjustments, values can be limited to safe regions. New pages of process schematics, trends and live data, can be generated when the system is on line. For purposes of redundancy two of the three CRT work stations can be switched between the host 11/44 and the 11/34 control computers. Figure 5 shows a typical page of refrigerator process graphics.

The control system has performed beyond expectations throughout the acceptance tests. The highly instrumented system, access to the data tables plus the ability to run FORTRAN calculations in parallel with the process logic permits detailed analysis of real time data throughout the testing period, a feature which here-to-fore was not available to the

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cryogenic engineer. Operator instructions and check lists are stored on disk and can be printed on demand.

1. D.P. Brown, et al; Cycle Design For the ISABELLE Helium Refrigerator in: "Advances in Cryogenic Engineering," Vol. 27, Plenum Press, New York (1982), p. 501.
2. Y. Farah and J.H. Sondericker, A Precision Cryogenic Temperature Data Acquisition System, presented at 1985 Cryogenic Engineering Conference, Paper FC-1.

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