Power Saving of Large-Scaled Helium Compressor for Fusion Device

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Abstract. For the purpose of reducing the power consumption of a cryogenic system for an experimental nuclear fusion system, investigation of the relationship between the ambient temperature and the mass flow rate of the compressor was carried out. When the suction gas temperature is lowered, gas density increases. The mass flow rate of the compressor can therefore be increased without any change in power consumption. It has been confirmed that some 5.6% of compressor power consumption can be saved by making the cooling water temperature equal to the ambient temperature during the winter season with the continuous running of the cooling tower fan motor. Further, a new gas compression cycle using an additional auxiliary gas cooling system was developed to lower the compressor suction gas temperature. Compared to a conventional system, some 11% of power consumption can be saved using this new gas compression cycle when the helium gas suction temperature of the compressor is 235K.

1. Introduction

The cryogenic system for a Large Helical Device (LHD) has an equivalent refrigeration capacity of 9.1kW at a 4.4K. The LHD uses eight sets of oil injection type screw compressor units manufactured by MYCOM. The total power consumption of these eight screw compressors is 3.45 MW at 1100 g/s mass flow rate. Since the nuclear fusion cryogenic system is kept in operation for each experimental cycle for long periods of time exceeding six months, power consumption savings is an important theme for LHD operation. In the case of the International Thermonuclear Experimental Reactor (ITER) project, continuous operation of the cryogenic system exceeds that required for LHD research. The need for power savings when operating the screw helium compressors of the ITER project is accordingly very important.

Taking the requirement for improvement in the power consumption into consideration, research and investigation was carried out using the LHD cryogenic system while monitoring changes in ambient temperature and cooling water temperature. This paper describes the results of research and investigation carried out with the experimental system for LHD with a view to improving power savings of the fusion cryogenic system.
2. Relationship between Suction Gas Temperature and Mass Flow Rate

A schematic flow chart of the compressor portion of the LHD cryogenic system is shown in Figure 1. The helium buffer tank is located outside the building, taking the influence of ambient temperature on gas temperature into consideration. The cold box is installed some 100m distant from the compressor machine room and connected through a piping pit (outside the building). The helium gas inside the connection pipe is also affected by ambient temperature. Research and investigation of the relationship and mutual influence between ambient temperature, gas mass flow rate and power consumption of the screw helium compressors were carried out with this LHD cryogenic system from August through December, 2003.

![Figure 1. Compressor system for the experimental fusion device, LHD](image)

The cryogenic system was operated steadily and the mass flow rate of helium gas to the cold box was constant during the period of this research and investigation. The ambient temperature and power consumption of group-A compressors and the opening stroke of the suction control valve (LCV1001A) were monitored as shown in Figures 2 and 3 below.

![Figure 2. Power consumption vs. Temp.](image)

![Figure 3. Valve stroke vs. Temp](image)

During the period of research and investigation, changes in ambient temperature from 301K through 278K and changes in the suction valve (LCV1001A) opening stroke from 75 through 81% were observed. This phenomenon means that the compressor mass flow rate rose according to changes in ambient temperature, because the mass flow rate to the cold box remained constant. On the other hand, power consumption of the compressor was constant during the research and investigation period.

This phenomenon is easily understood using theoretical gas compression power. The formula for isothermal compression power is shown below.

\[ PV = nRT \]  \hspace{1cm} (1)

\[ W_{iso} = P_1 V_1 \ln(P_2/P_1) \]  \hspace{1cm} (2)

Compression power \( W_{iso} \) is proportional to the actual gas flow rate \( V_1 \), as shown in formula (2). Since the suction gas density is inversely proportional to the gas temperature, as shown formula (1),
the compression power for the unit mass flow $W_{\text{win}}/n$ is proportional to the suction temperature. This means that “Low suction gas temperature leads to low compressor power consumption,” which is a very important suggestion for future improvement of large-scale cryogenic systems such as the ‘ITER’ nuclear fusion program.

3. **Power saving of cryogenic system with new compression cycle**

Low suction gas temperature is effective as a power saving measure for compressor systems. On the other hand, additional power is required to cool down the suction gas. Optimization of the gas temperature and a comparison of optimum system configurations should be discussed with a view to minimizing total power consumption. Supposing that the operating conditions of the low temperature side for the first heat exchanger inside the cold box are constant and the heat exchanger is isolated from the external temperature, it is obvious that the low pressure return gas temperature (LP) and the medium pressure gas temperature (MP) can easily be lowered by cooling down the supply gas temperature (HP). Putting an ammonia refrigerator on the compressor discharge side, high cooling down efficiency can be obtained compared to installing on the compressor suction side. Table 1 shows a comparison of three different scenarios, cited the refrigeration system of 18kW at 4.5K of CERN/LHC [1], which is regarded as the reference for the refrigeration system of the ITER project. The pressure, temperature and mass flow rate of each stage is shown in Table 2. The isothermal compression power consumption was 2.40MW and the isothermal compression efficiency was 57.1% in total for all compressors. The power consumption for individual helium compressors was calculated while neglecting changes in suction gas temperature and changes in isothermal efficiency.

![Figure 4. Schematic flow of modified helium compressor cycle](image)

| Table 1. System configuration of compressor system | Table 2. Standard compressor model |
|---|---|
| **Conventional** | **Case** | **Case** | **Case** | **LP mass flow** | **800 g/s** |
| **LP press./temp.** | **0.105 MPa/ 300 K** |
| **MP mass flow** | **880 g/s** |
| **MP temperature** | **0.39 MPa/ 300 K** |
| **HP mass flow** | **1680 g/s** |
| **HP temperature** | **2.0 MPa/ 313 K** |
| **Power consumption** | **4.21 MW** |

| C.W. temp control | O | --- | O | O |
|---|---|---|---|---|
| Chemical heat pump | --- | --- | O | O |
| NH3 refrigerator | --- | --- | O | O |

3.1. **Study of water temperature control (Case 1)**

In general, the temperature of the cooling water (C.W.) is controlled to prevent freezing during the winter season. Temperature control of the cooling water leads to considerable power savings due to partial stoppage of the fan motors of the cooling tower. On the other hand, continuous running of cooling fan lowers the water temperature. The temperature of HP gas, LP gas and MP gas also goes down because the heat balance of the 1st heat exchanger. The compressor suction volume against the same mass flow rate also goes down, allowing miniaturization of the compressor become available while assuring considerable power saving in winter.
The water temperature and gas temperature for each stage and compressor power is calculated using the ambient temperature investigated at NIFS/LHD (Shown in Figure 2.) The temperature of each stage is shown Table 3. The power of fan motor is calculated as it is the 0.4% of heat load. We assumed the power reduction rate for the fan motor is 70% in winter.

We confirmed that the power consumption drops from 4.23 to 3.99MW, and the efficiency of the cryogenic system becomes 5.6% higher when the cooling tower fan continues to be operated compared to temperature control of the cooling water in winter as shown in Table 4.

**Table 3. Comparison of temperature condition**

|                | Ambient temp. | Cooling water | Gas temperature |
|----------------|---------------|---------------|-----------------|
|                | (DB) (K)      | Supply (K)    | Return (K)      | HP (K) | MP (K) | LP (K) |
| Conventional   | Summer        | 301           | 303             | 308    | 313    | 300    |
| Conventional   | Winter        | 278           | 303             | 308    | 313    | 300    |
| Case 1         | Winter        | 278           | 303             | 287    | 296    | 283    |
| Case 2         | Summer        | 301           | 303             | 308    | 263    | 250    |
| Case 3         | Summer        | 301           | 303             | 308    | 247    | 234    |

**Table 4. Comparison of power consumption**

|                | LP (MW) | HP1 (MW) | HP2 (MW) | Fan (MW) | Chem. (MW) | NH3 (MW) | Total (MW) |
|----------------|---------|----------|----------|----------|------------|----------|------------|
| Conventional   | Summer  | 1.15     | 1.49     | 1.57     | 0.02       | ---      | 4.23       |
| Conventional   | Winter  | 1.15     | 1.49     | 1.57     | 0.01       | ---      | 4.21       |
| Case 1         | Winter  | 1.08     | 1.41     | 1.48     | 0.02       | ---      | 3.99       |
| Case 2         | Summer  | 0.96     | 1.50     | 1.31     | 0.02       | 0.21     | 3.99       |
| Case 3         | Summer  | 0.91     | 1.36     | 1.23     | 0.02       | 0.04     | 3.76       |

3.2. Study of forced cooling by additional refrigerator (Case 2,3)

We applied a chemical heat pump for primary gas cooling to save energy loss, as shown in Figure 4. An NH3 refrigerator is located after the chemical heat pump. Since annual power saving is the purpose of this study, an ambient temperature 301K is used for this calculation. The pressure drop of the heat exchanger will lead to inclemency in the discharge pressure. A 0.01 MP pressure drop for each heat exchanger is added. The power of each compressor is calculated using the ratio of isothermal compression power. Power consumption of the chemical heat pump is calculated at a COP of 10 [2]. The power of the NH3 refrigerator is calculated as the Carnot efficiency is 45%.

We confirmed that the power consumption drops from 4.23 to 3.99MW and the efficiency of the cryogenic system becomes 5.6% higher when the suction gas temperature is 250K when we use the Case 2 cycle. We also confirmed that the chemical heat pump is very effective in improving efficiency. Power consumption drops from 4.23 to 3.76MW and the efficiency of the cryogenic system becomes 11% higher when the suction gas temperature is 235K if we use the Case 3 cycle.

4. Conclusions

As a result of these comparisons, we concluded the following:

(1) 5.6% of power will be saved in winter by running the cooling tower fan continuously.

(2) 11% of power will be saved annually by using a chemical heat pump and an NH3 refrigerator.

This system is very effective in reducing the power consumption of a cryogenic system. We will continue to investigate the efficiency of the compressor in detail and results will be reported soon.

References

[1] Gruehagen H and Wagner U 2004 JCEC20 TuOA-3(No.206)
[2] Nobuya I and Hiroyuki S 2003 JSRAE Symp. B211-1