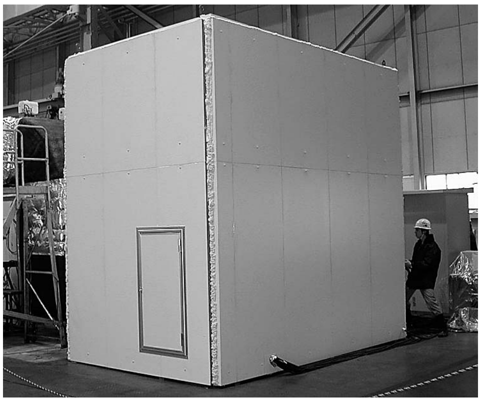

# Development of Air Cycle System for Refrigeration

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*Mitsubishi Heavy Industries, Ltd. (MHI) has developed the most environment-friendly, easiest to use, and maintenance minimized system that has superior operating performance at −50°C or lower. It has been attributed to three features. The First is the single shaft with an expansion turbines, compressor and a built-in motor. The Second is the oil-free turbo machine with an active magnetic bearings. The Third is inverter controlling for revolution. MHI has successfully made it possible not only to minimize power consumption but also maintenance. Besides, low pressure (maximum: 0. 1 MPa) also leads to easy to use.*

## 1. Introduction

Due to concerns of the ozone hole, CFC and HCFC had been banned and then, HFC has been developed as the alternative. Recently, however, due to concerns of global warming, natural refrigerants have been focused and beginning to be available commercially. In these situations, practical researches of an air cycle are being conducted. The conventional vapor compressors are based on the utilization of the latent heat of the refrigerant. In contrast, an air cycle system is operated in the only gaseous state, accordingly, the latent heat value is not used. Consequently, it is at −55°C or lower that the power consumption of air cycle is lower than them. As natural refrigerants of these low temperature range, ethane and ammonia are also available in the dual compressor, however, these have risk for toxicity and combustibility. Air is non-toxic, non-flammable, therefore easiest to handle.

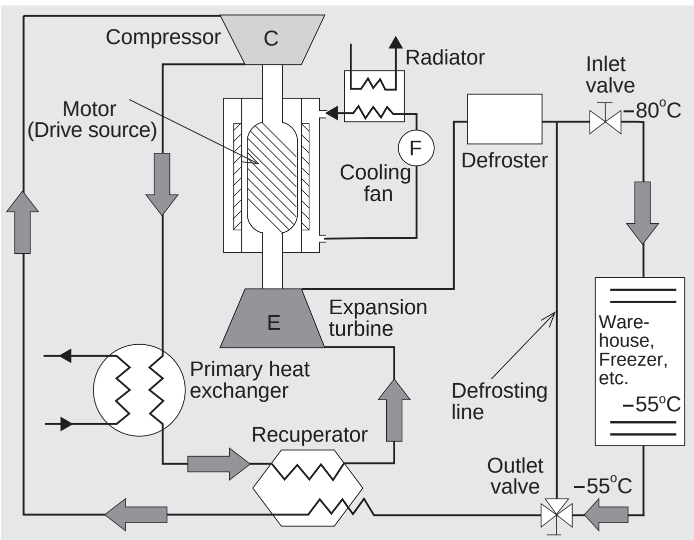


**Fig. 1 System diagram of Air Cycle System**
Schematic diagram showing the process for the air cycle developed by MHI.

MHI has developed the air cycle and presents technical details in this paper. The air cycle is realized Low Life Cycle Cost (LCC) adopting single shaft turbo machine consisted of the expansion turbine, compressor and built-in motor. Furthermore, the active magnetic bearing contributs to low LCC, by minimizing the maintenance. In addition, the system is also user-friendly working at maximum 0.1 MPa, compared with conventional vapor compressors.

## 2. Air cycle system

### 2.1 Outline of the system

**Fig. 1** shows the schematic diagram of the system, while **Table 1** shows the principal specifications. The turbo machine in the principal portion consists of a compact single shaft that combined with the turbine that produces low temperature air by expansion, the compressor that raises the pressure of the air to be introduced in the turbine, and the built-in motor that supplements the drive force.

In addition to the turbo machine, the air cycle system also consists of three parts. The first is the recuperator to exchange refrigerated air from the warehouse to heated one after pressurized. The second is the heat exchanger for cooling air coming out of the compressor. The third is the defroster for hygroscopic moisture in the system. If the temperature and the thermal load in the warehouse are determined, the temperature and pressure in each part of the system should be uniquely determined. In addition, another line for defrosting is set up in the system.

Table 1 shows the heat balance at −55°C in the warehouse. The maximum pressure of air in the system is 0.1 MPa, The highest and lowest temperatures are +125°C, and −80°C respectively, and refrigeration capacity is 42 kW, and the overall system COP (Coefficient of Performance) is the value of 0.44.

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**Table 1 Specifications of Air Cycle**

| No | Item | Specification | Remarks |
|---|---|---|---|
| 1 | Refrigeration capacity | 42 kW (Warehouse temperature: –55°C) | |
| 2 | Maximum output of motor | 100 kW | |
| 3 | Rated number of revolutions | 21 000 rpm | |
| 4 | System COP | 0.44 (Warehouse temperature: –55°C) | Including auxiliary |
| 5 | Pressure | Maximum 0.1 MPa (Gauge) | |
| 6 | Dimensions | W 2 300 × L 2 950 × H 3 400 | Including soundproof panels |
| 7 | Weight | Approximately 5.5 tons | Including soundproof panels |
| 8 | Noise | 70 – 80 dB (A) | |

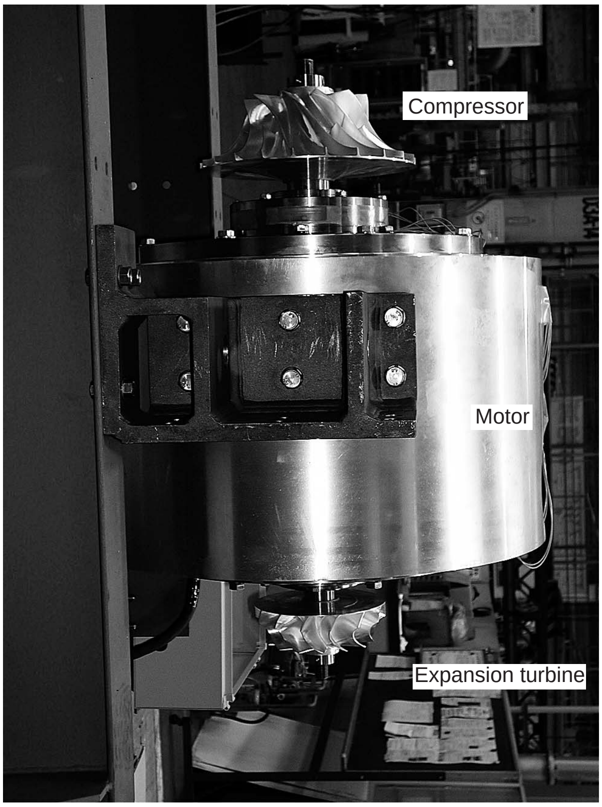


**Fig. 2 Photo of single-shaft oil less turbo machine**
The compressor is located in the upper portion, while the expansion turbine is located in the lower portion. The motor and magnetic bearing are set in between.

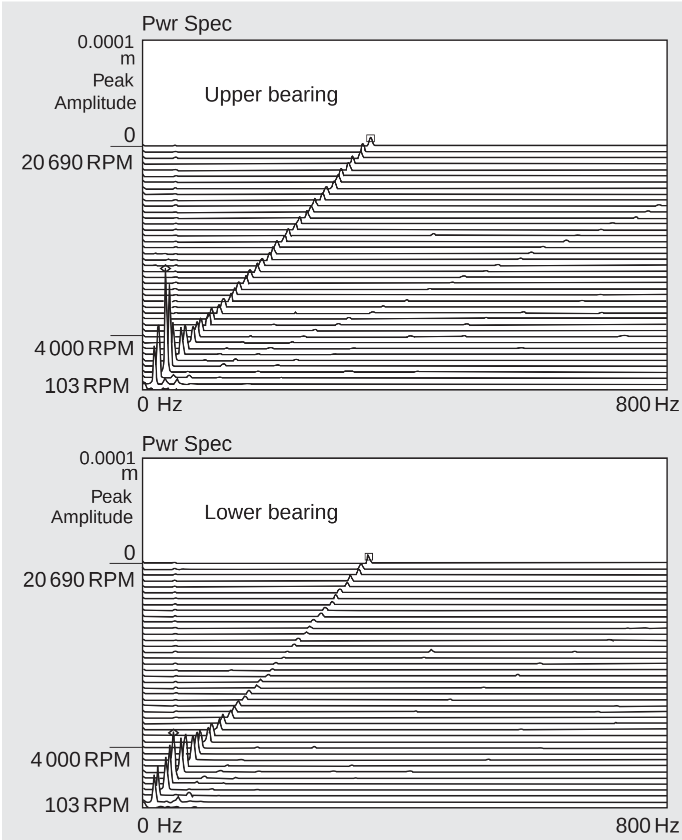


**Fig. 3 Shaft vibrations, raising the speed of turbo machine**
Shaft vibration becomes small after 4 000 rpm of the critical range.

### 2.2 Outline of the turbo machine

As shown in **Fig. 2**, the turbo machine is made up of components with characteristics that include

(1) Highly efficient impeller of turbine/compressor for micro gas turbines, based on the supercharger technology;

(2) Highly efficient, synchronous, built-in motor with permanent magnet

(3) Minimum-loss, non-lubrication, non-contact and fully active magnetic bearings used for turbo-molecular pumps.

The existent air cycles are necessary two-stage. However, with these technologies integrated, MHI has been able successfully to develop the vertical, highly efficient turbo machine, which is the single shaft working at 21 000 rpm in the maximum revolution of 100 kW motor.

Furthermore oil-free and, variable speed operations with the inverter have been realized. Besides, the turbo machine is designed to pass the critical speeds of the rigid mode in lower speed and operate sufficiently under the critical speeds of the elastic mode. Then, this has high reliability concerning vibration over variable speed operation.

**Fig. 3** shows the three-dimensional analysis result indicated the actual measurement of the shaft vibrations, in the progress of raising the speed. As it is clear from the figure, the machine passed critical speed until reaching at 4 000 rpm, after that, was able to steadily operate until reaching at the maximum revolution.

### 2.3 Features of the system

The features of the air cycle based mainly on the turbo machine are summarized below. **Fig. 4** shows the photo of the air cycle that was fabricated for outdoor-setting.

- Using readily air as refrigerant and operating low pressure allow the users easier to handle, especially for refrigerant leak.
- Complete oil-free system enables users to have no concerns of splashing it.
- Inverter controlling enables users to minimum power consumption, adjusting automatically to the designated temperature
- Lower LCC at −50°C or lower and lower power consumption at −60°C or lower
- Variability of operation from −100°C to −20°C due to utilize the only latent heat value of the refrigerant. This enables to backup, in case of troubling the other system operating in tandem at the different temperature
- Approximately same power consumption between direct and indirect with the secondary refrigerant system.

**Table 2** showed comparison of the characteristics between air, ammonia and ethane.

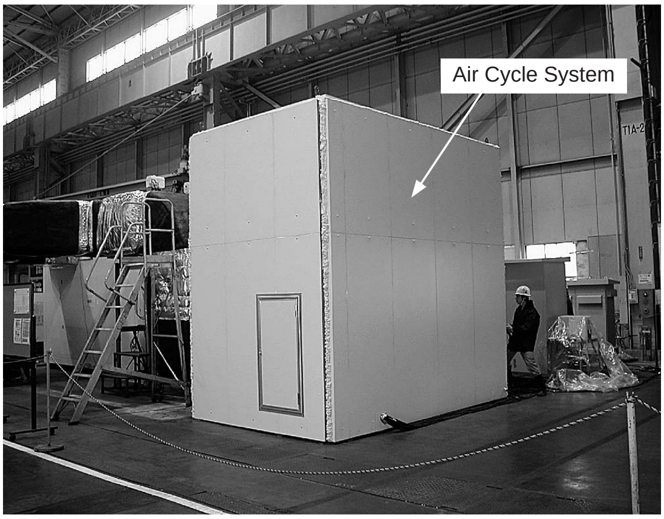


**Fig. 4 Photo showing the air cycle**
Photo shows the system fabricated with the soundproof covers for outdoor.

**Table 2 Comparisons with Characteristic of Handling**

| | Air | Ammonia | Ethane |
|---|---|---|---|
| Toxicity | None | Present | None |
| Combustibility/ flammability | None | Present | Present |
| Corrosiveness | None | Present | None |
| Working pressure | Low pressure About 0.1 MPa | High pressure About 1.5 MPa | High pressure About 1.5 MPa |
| Total Risk | Low | High | High |

## 3. Refrigeration performance

### 3.1 Evaluation of the power consumption

**Fig. 5** shows the comparison of the power consumption of the air cycle to two-stage R22 compressor at −30°C, to dual $NH_3$/R23 compressor at −55°C, and to liquid nitrogen at −80°C respectively. It turns out to be that power consumption of the air cycle ends up approximately twice more at−30°C, almost equivalent at −55°C, and further better one eighth less than at −80°C.

### 3.2 Evaluation of LCC

As the case of **Fig. 5**, **Fig. 6** shows the LCC the comparison of the air cycle to a two-stage R22 compressor at −30°C, to a dual $NH_3$/R23 compressor at −55°C, and to liquid nitrogen at −80°C. LCC consists of initial cost and operation cost for 15 years, including power and maintenance. LCC of the air cycle results in less than a dual $NH_3$/R23 compressor at −55°C and further better one forth less than at −80°C.

It can be also seen from **Fig. 6** that LCC of the air cycle is less than conventional vapor compressors and liquid nitrogen at −50°C or lower.

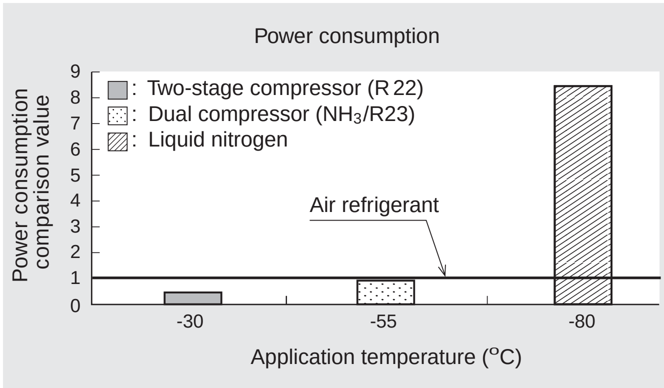


**Fig. 5 Comparison of power consumption**
Power consumption of the air cycle ends up, almost equivalent at −55°C, and further better one eighth less than at −80°C.

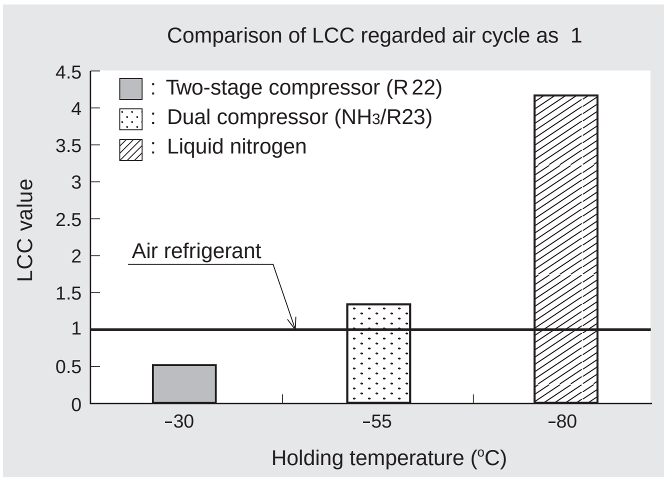


**Fig. 6 Results of evaluation of LCC comparison**
The LCC of the air cycle result in less than the dual $NH_3$/R23 compressor at −55°C and further better, one forth less than liquid nitrogen at −80°C.

## 4. Test results

To verify performance, controllability, automatic operating, durability, defrosting and other factors, operating tests were carried out aimed at the warehouse (3 600 mm long x 2 700 mm wide x 3 625 mm high) in Fig.4.

The following were verified as the result of the tests.

- Stable operations while avoiding surging, etc. until reaching 21 000 rpm as the full load
- Capability of outputting targeted refrigeration capacity at the designated temperature, while giving the thermal load into the warehouse
- Controllability for various wave of thermal load in the warehouse, based on smoothly controlling of the revolution
- Capability of defrosting and draining frozen moisture rising in the warehouse
- Capability of Automatically operating for starts & stops, for full & part loads and for defrosting
- Capability of varying the temperature according to demand, therefore, back upping if operating in tandem
- Capability of reducing the noise in the level of 70 dB (A) if installed soundproofing panels; refer to Fig. 4

In addition, remote monitoring system has been developed prior to the field-testing.

## 5. Conclusion

MHI has developed the oil free, clean refrigeration system in less LCC including the cost of initial , power and maintenance at $-50^{\circ}$C or lower. Using the only natural air is indicated both environmentally- and user-friendly. Performance and reliability of the system had been verified through actual in-house testing. MHI plans field-testing in actual working warehouse for tuna, with the aim of enhancing its reliability and durability even further.

Since 2003, this air cycle was nominated for ICETT (International Center for Environmental Technology Transfer Association in Japan) Investment and received subsidies because it was permitted to make huge contributions to prevent from global warming. MHI and the authors would like to extend their deepest appreciation to each of the persons that provided invaluable cooperation and support in this research.

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