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A High Reliability Gas-Driven Helium Cryogenic Centrifugal Compressor

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Abstract

A helium cryogenic compressor was developed and tested in real conditions in 1996. The achieved objective was to compress 0.018 kg/s Helium at 4 K @ 1000 Pa (10 mbar) up to 3000 Pa (30 mbar). This project was an opportunity to develop and test an interesting new concept in view of future needs. The main features of this new specific technology are described. Particular attention is paid to the gas bearing supported rotor and to the pneumatic driver. Trade off between existing technologies and the present work are presented with special stress on the bearing system and the driver. The advantages are discussed, essentially focused on life time and high reliability without maintenance as well as non pollution characteristic. Practical operational modes are also described together with the experimental performances of the compressor. The article concludes with a brief outlook of future work.

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A HIGH RELIABILITY GAS-DRIVEN HELIUM CRYOGENIC CENTRIFUGAL COMPRESSOR.

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ABSTRACT

A helium cryogenic compressor was developed and tested in real conditions in 1996. The achieved objective was to compress 0.018 kg/s Helium at 4 K @ 1000 Pa (10 mbar) up to 3000 Pa (30 mbar). This project was an opportunity to develop and test an interesting new concept in view of future needs. The main features of this new specific technology are described. Particular attention is paid to the gas bearing supported rotor and to the pneumatic driver. Trade off between existing technologies and the present work are presented with special stress on the bearing system and the driver. The advantages are discussed, essentially focused on life time and high reliability without maintenance as well as non pollution characteristic. Practical operational modes are also described together with the experimental performances of the compressor. The article concludes with a brief outlook of future work.

INTRODUCTION

In order to boost the capacity of the 1.8 K test stand at CERN, a single centrifugal cryogenic compressor called CCU (Cold Compressor Unit) was manufactured. It enabled to triple the available cooling power and flow rate from 0.006 to 0.018 kg/s. It was also a good opportunity to test new technologies for future use in LHC project. Therefore, the approach to this work was to develop and test all potentially interesting ideas for LHC. In other words, the design was chosen more to investigate future options rather than strictly answering at best profit and efficiency the needs of the test stand.

SPECIFICATIONS

The nominal design point of the compressor was specified to reach the values of Table 1. Moreover, reduced flow cases were considered and specified according to Table 2.

MAIN DESIGN OPTIONS

The compressors such as those Air Liquide earlier delivered to CEBAF (now TJNAF), are still a reference of cryogenic centrifugal compression and have been giving full satisfaction since 1993. These machines, pumping up to 240 g/s from 2.8 kPa at 4.32 K up to 115.4 kPa, use electrical drive and bearings. The journal and thrust supports are active magnetic bearings and the drivers are electrical motors. Such a design normally results in relatively costly electronic cabinets and hardware while the time between maintenance is equivalent to good electronic quality standards.

The options for the CCU were very different. It is designed as an essentially pneumatic machine. The bearings are externally pressurized bearings from a standard Air Liquide type C6 expansion turbine. The driver is a centrifugal expansion turbine with 3 tangential outlets. Another major difference is that the machine has a cartridge design (i.e. : it can be extracted from the cold box relatively easily, without breaking the vacuum insulation.). These two features are normally found on all Air Liquide expansion turbines. However, they are totally innovative on cold compressors.

A priori, the following advantages can be foreseen. First, high rotational speeds are available with little practical limitations. Second, there is a significant reduction in investment cost: gas bearings are certainly cheaper than active magnetic bearings together with their electronics, and so is the expansion turbine compared to the motor together with its frequency converter. The reliability is already proven to a very large extent since the core of the machine is identical to that of existing expansion turbines (see Figure 2), which have accumulated years of continuous operation without any need for maintenance. The operation is also very simple. It is only necessary to make sure there is pressure inside the gas bearings (turn a valve on) and the compressor is ready to run at any speed without any special additional precaution. Of course, the gas bearings themselves do not introduce lubricant of any sort (as ball bearings could do for example) since they operate with the helium of the cycle.

Table 1. Specified performance in nominal condition

	Inlet	Outlet
Temperature (K)	3.5 to 4.4	to be minimized
Pressure (Pa)	1000	3000
Flow rate (kg/s)	0.018	
Isentropic efficiency	≤ 60%	

Table 2. Specified performance at reduced flow

	Inlet	Outlet
Temperature (K)	4 ± 1 K depending on flow and operation	to be minimized
Pressure (Pa)	1000	see curve attached on Figure 1
Flow rate (kg/s)	0.006 to 0.018	

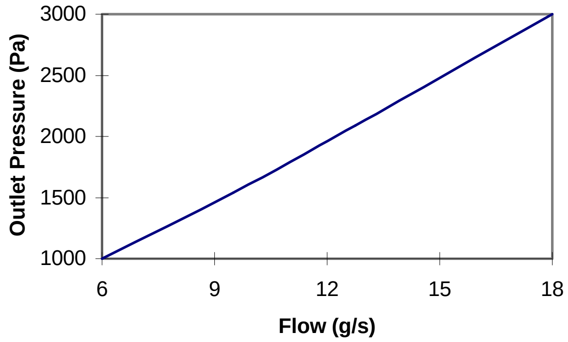

Figure 1. Outlet pressure versus flow rate

However, these technical choices also bring some drawbacks. With pressurized bearings, the low pressure on one side of the shaft is about 100 kPa, a lot higher than the back-wheel pressure, which is close to 2 kPa. Leaks of warm 300 K helium from the bearings to the 10 K wheel would have a catastrophic effect on the outlet temperature of the cold compressor. A special non-contact seal has therefore been designed. The compressor drive makes uses of helium at high pressure as utility, which must be made available at reasonable cost.

The use of a pneumatic machine was not strictly necessary for the CCU. The maximum operating speed (below 400 Hz), together with the low requirements on reliability, were still in the range which can be covered by ball bearings and electrical motor. However, in view of the development goals of such machinery for the LHC project, pneumatic drive and bearings have been chosen.

COMMISSIONING

Measurements

Commissioning of the compressor took place at CERN. The quality of pressure and temperature measurements were first assessed. It was not so trivial to measure very low temperature with such a low density fluid 1000 Pa (10 mbar). We give in Table 3 our estimate of the precision of the measurements at compressor inlet.

Table 3. Estimated precision of the measurements

	Nominal value	Precision around nominal	Range
Pressure (Pa)	1000	0.5%	0-5000
Temperature (K)	4	$\pm$ 0.05K	3-10

Compressor Performance

It became very soon clear that the thermal performance of the supporting structure at low temperature was insufficient. This resulted in larger heat leaks than the available envelope and to negative blade tip clearance. This problem was solved by insertion of a vacuum insulation space inside the compressor itself and reevaluation of the blade tip clearance. This internal vacuum insulation was an improvement to the standard Air Liquide expansion turbines, which normally do not request such techniques. This improvement lowered the heat leaks to the cold helium to 35 W in total, an adequate value for such a machine.

In search of compactness, the inlet pipe and general dimensions of the machine were reduced to minimum. The tests showed that the design had gone a little too far in this direction : in some places, sonic conditions were reached, thus preventing to reach good efficiency and pressure ratio. We implemented some minor modifications which enabled to reach the desired pressure ratio of 3 at 0.018 kg/s. The maximum efficiency reached 57% despite the fact that we could change neither the general dimensions of the machine nor the inlet pipe. To give an idea how stringent the constraint on the inlet pipe size has been, we foresee an improvement of the efficiency of the machine of approximately 10% with a larger inlet pipe.

The non-contact seal performed remarkably and no influence of the leak on the efficiency could even be detected. This corresponds to leak of the order of 10^{-6} kg/s warm helium.

OPERATION

The operation of the compressor proved straightforward. To achieve cool down, the bypass valve was progressively closed while more and more helium was sent into the free-wheeling compressor. The shut down of the by-pass valve was controlled so that moderate quantities of gas were passed through the compressor : its free-wheeling rotational speed was kept below 120 Hz. Once the compressor was cold and the by-pass valve shut, the rotational speed was simply increased by opening the control valve of the pneumatic drive. The pressure ratio then increased continuously together with the flow. This was repeated until the nominal design point was reached. The user interface for this operation is a simple pressure set point : the system automatically adjusts the speed by means of the control valve.

Warm up was also simple : the speed set point is set to 0, the by-pass valve is opened, the inlets and outlets of the compressor are closed and warm helium is circulated through the machine.

The surge line was relatively close to the nominal operating point, due to the fact that the modifications described above had to be implemented to compensate for the over-compactness of the machine. However, there has not been any unexpected surge nor stability problem during the operation of the compressor. The compressor has shown good stability when submitted to fast change of its operating point. It was tested to automatically withstand changes from 0.016 to 0.01 kg/s and would probably show similar easy behavior over the whole flow range (0.006 to 0.018 g/s).

The bearings have shown excellent availability and robustness to all operating and test conditions. Whatever the temperature of the compressor wheel, the bearings could withstand any sort of positive or negative acceleration. There was a wide margin towards higher speeds if needed. There was no forbidden, so called "critical", speed to be specially avoided during operation. No maintenance of the bearings was needed after operation, and we do not foresee any in the long term. In fact, the bearings being identical to standard expansion turbines, there is no reason their life time is not identical. (The standard turbines have proven life time above 40000 hours and they have not met any hard limitation yet). The helium consumption in the bearings is of the order of 0.0018 kg/s. In order to save high pressure helium gas as utility, the driver (0.006 kg/s at maximum output torque) and the bearings can be put on the same line rather than in parallel.

FURTHER DEVELOPMENTS

Non Contact Seal

The seal between the bearings and the compression wheel is critical. The present design of the seal makes use of an intermediate-pressure chamber, evacuated by a vacuum pump. This is not in the general idea of no-maintenance compressors, although such maintenance (less than every 10 000 hours anyhow) would be easy and would never endanger the system. As an interesting alternative, a special, non-contact seal requiring no external pumping has been designed. It is now under construction and will be installed for tests. It should ensure good tightness through small auto-adaptive clearance. The residual leak will be of the order of a few 10^{-6} kg/s warm helium (corresponding to a few Watts at 4K)

Tolerant Diffuser

The actual design has a high-density diffuser with numerous, thin blades. This promotes efficiency against flexibility. The compressor will be tested with bladeless diffuser.

Drive

For more powerful machines, a different expansion turbine drive must be used. The centrifugal expansion turbine is well adapted for low power, such as for this CCU. For higher power and better efficiency, normal centripetal turbines are better suited. For this kind of machines, the more powerful the turbine, the easier to design and build.

3D wheel

The use of axial-centrifugal wheels can be well suited for this kind of machine. Although they often require higher rotational speeds (which the gas bearings can provide easily), they offer significant reduction of size and therefore, minimization of heat leaks. Such a wheel should be implemented and tested on the CCU. Design of future machines for LHC could also make use of such wheels.

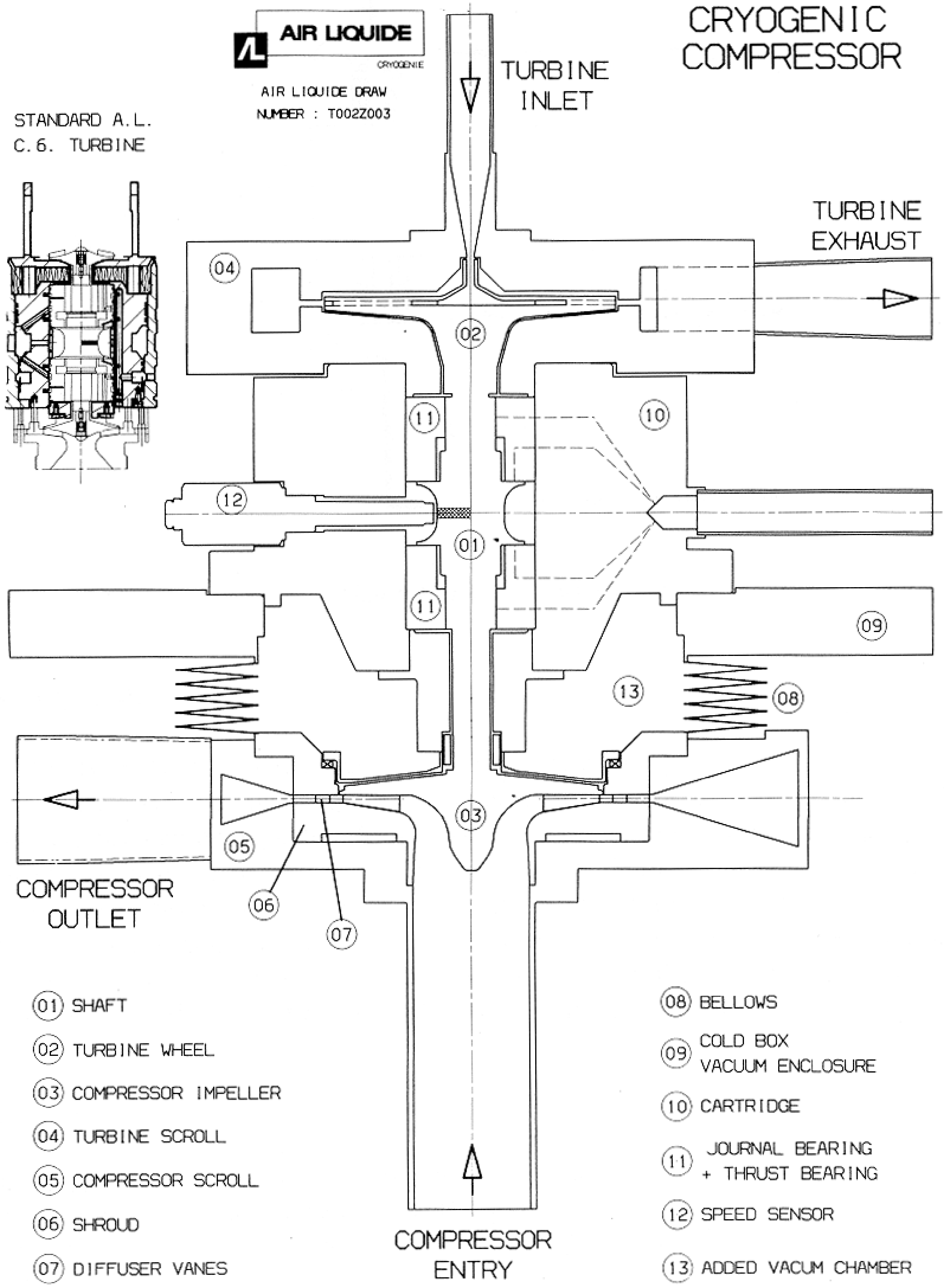

Figure 2. Schematic view of cold compressor

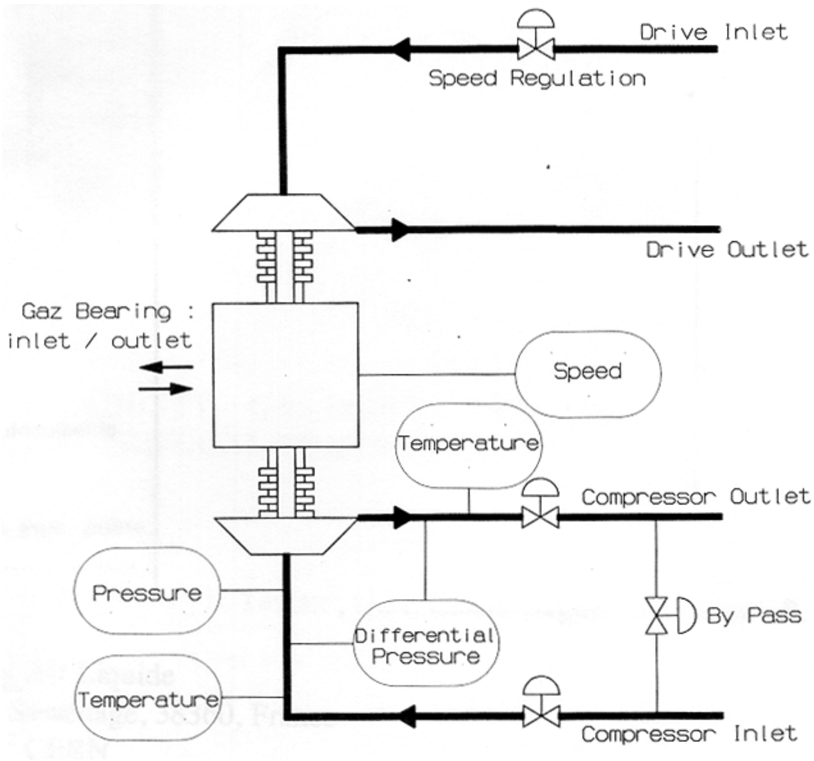

Figure 3. Overall system scheme

CONCLUSION

This type of pneumatic centrifugal cryogenic compressor is very well suited for high-reliability systems that require moderate investment cost. Many years continuous or intermittent use can be expected. It is suitable for use at higher rotational speeds than either advanced ball bearings or magnetic bearings can provide today. Wherever both pneumatic or alternative technology can be used (i.e. : lower speed and lower reliability), trade off shall be carried out to determine whether it is economically interesting to choose lower investment (gas bearings) with more helium utility consumption in the long term or more expensive electrical systems that do not require helium utility at all.

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