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Application of Trunk Piston Labyrinth Compressors in Refrigeration and Heat Pump Cycles

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ABSTRACT

The effect of global warming and ozone depletion calls for better recovery and utilization of waste heat just when some of the most commonly used fluorocarbon refrigerants are being judged unsuitable.

Ammonia has been known for a long time as a very effective refrigerant. Due to its hazardous nature, ammonia has been replaced by the CFC's except for large industrial refrigeration systems. Since standard lubricants are not soluble in ammonia, oil in the refrigerant will foul heat exchangers and therefore reduce their efficiency. The oilfree compression of the refrigerant is particularly important in refrigeration systems with temperatures in the evaporator below - 40°C.

Based on the experience with Labyrinth Piston compressors of the crosshead type, a less expensive Trunk Piston Labyrinth compressor for technically oilfree compression has been designed, manufactured and applied in refrigeration and/or heat pump cycles with ammonia as a refrigerant.

INTRODUCTION

Hazardous effects like toxicity and flammability led to the replacement of ammonia as a refrigerant except for industrial refrigeration systems. Recent publications show, that ammonia might gain back higher market shares as an alternative to chlorofluorocarbons (CFC's). Ammonia does not affect directly global warming or add to the depletion of the stratospheric ozone. In addition, the technology required for the design of refrigeration systems with ammonia is well known.

Labyrinth piston compressors of the crosshead type have been successfully applied in refrigeration and/or heat pump cycles for many years. Design features like oilfree compression, gas and pressure tight crankcases allow for safe operation and low maintenance cost.

This paper describes a newly designed Trunk Piston Labyrinth (TPL) compressor. Special emphasis will be given on the technically oilfree compression and the gas and pressure tight crankcase design with its impact on safe and cost efficient maintenance. A typical application of a TPL in a heat pump cycle with ammonia as a refrigerant will be presented in the second section.

DESIGN FEATURES OF THE TRUNK PISTON LABYRINTH COMPRESSOR

An oilfree compression of the refrigerant can be obtained in two ways. One possibility is the dynamic seal between piston and cylinder, another is the use of piston rings which require no lubrication. In the second case, the sealing is static, as it is also when lubricated piston rings are used. Sealing between piston and cylinder can also be obtained without the piston touching the cylinder wall. For this purpose, the outer skirt of the piston and/or the internal wall of the cylinder are provided with fine grooves, as shown in Fig. 1 [1]. The small clearance between piston and cylinder wall offers a considerable resistance to the passage of the gas, this resistance being further increased by the labyrinth action of the grooves. A big advantage of this dynamic sealing is the frictionless movement of the piston in the cylinder.

In a crosshead type labyrinth compressor, the piston rod is fitted accurately in the crosshead and in a special guide bearing. Because of this arrangement, the piston - of self centering design - moves without vibrating and without touching the cylinder wall (Fig. 2). Sealing of the piston rod with respect to the cylinder is carried out by means of a stuffing box, which is also provided with grooves and operates without making actual contact with the piston rod.
An oil scraper ring, fitted above the guide bearing, prevents the passage of oil along the piston rod into the stuffing box. In order to prevent any oil film of molecular thickness that may possibly form on the piston rod from penetrating into the cylinder, the distance between guide bearing and stuffing box was chosen to be of such a magnitude that the wetted portion of the piston rod does not move into the cylinder.

The Trunk Piston Labyrinth compressor has been derived [2] from the crosshead type compressor by omitting the piston rod, the stuffing box, and by joining the labyrinth piston and the crosshead (Fig. 3). As a consequence the piston is no longer double acting and the oil scrapers have been rearranged. Instead of two separate valves a concentric one has been chosen. This allows for a theoretically higher efficiency, due to the smaller clearance volume.

Working principle of a TPL

The labyrinth seal can only work if there is a leak gas flow between the cylinder and the piston. The leak gas of all stages is - in the case of the TPL - fed back to the suction side of the compressor by a special pipe (Fig. 4). Since the compressor is of the gas and pressure tight design and no pressure differential over the guiding part of the piston should occur, the volume of the crankcase is also connected to the suction side of the compressor. This means that the crankcase is always under suction pressure. For safety reasons, a demister is built into the leak gas line. Any oil mist from the crankcase or from the leak gas volume will be held back in the demister.

Technically oil free compression of gas in a TPL

The design of the above described TPL is only successful, if it is possible to prevent oil from spreading into the upper part of the cylinder. The lower part of the piston has therefore been equipped with a set of oil scrapers (Fig. 5). The piston is provided with small holes between the scrapers to allow the scraped off oil to flow back into the crankcase. Under operating conditions the leak gas volume stays dry. Measurements of the oil concentration in the compressed gas showed values well below 1 ppm. These measurements were confirmed by TPL's running under field conditions. If there is a small amount of oil in the compressed gas, the cylinder, labyrinth part of the piston and the valves would be wet, which is not noticeable even after several thousand running hours.

Gas and pressure tight crankcase

The application of the TPL in refrigeration systems or for difficult gases requires a gas- and pressure tight crankcase. The crankcase of the TPL is designed for 16 bar working pressure. The crankcase has therefore been designed as one piece, to avoid a complicated and most likely, not reliable sealing between the base plate, the upper part of the crankcase and the shaft. The rotating shaft is sealed with a mechanical shaft seal (Fig. 6). This seal is identical to the proven design applied in the crosshead compressors.

Cooling systems

The oil pump is integrated in the crankcase and directly driven by the crankshaft. The oil is filtered before and after the oil pump. The mechanical shaft seals, the lower and upper connecting rod bearings are supplied with pressurized oil, and the main crankshaft bearings and the guiding parts of the pistons are splash lubricated. An oil cooler is necessary in most cases.

The cylinders are water cooled. The cooling of the lower part of the cylinder keeps the clearance between the guiding part of the piston and the cylinder under all running conditions constant.

Layout of the TPL

Lab tests have shown that discharge pressures up to at least 200 bars can be realized. Until now only units with far lower discharge pressures have been installed in the field. Three types of compressors with 100 to 125 mm stroke are available. This allows for flows of about 500 Nm³/h with two first stage cylinders. Up to six single cylinders can be mounted on one crankcase.
WASTE HEAT RECOVERY WITH A HEAT PUMP IN A HYDRO-POWER PLANT

The hydro-electric power plant in Wettingen (Switzerland) is equipped with three turbines. The generators, the transformers and the bearings of the turbines have to be cooled. The purpose of the heat pump within the power plant is to provide energy for heating and for the production of hot water.

Concept

The concept of the optimized waste heat recovery is based on the availability of the amount of waste heat, the temperature of the waste heat and the demand for energy as a function of the outside air temperature. In wintertime the available waste heat is the limiting factor, whereas in summertime the demand for energy of the nearby Highschool and apartements govern the heating power of the heat pump.

Ammonia has been chosen as a refrigerant to avoid any risk of depleting the ozone layer and possible chemical reactions of the CFC's in the case of fire in the generator.

Considering all the above mentioned aspects the heat pump system has been designed as follows:

- Cooling power (= power of waste heat) 310 kW
- Heating power 400 kW
- Two single stage, oilfree compressors
  - Suction pressure 7.8 bar (17°C)
  - Discharge pressure 28.8 bar (64°C)
  - Nominal shaft power 52 kW (each)
- Expected average coefficient of performance (COP; ratio between heating power and supplied electrical power) 4.2

The compressors (see Fig. 7) are driven by electric motors with variable speed. The control system operates the compressors in parallel, or separately, at full speed or at preset speeds, depending on the required heating power.

To avoid any possible reactions of ammonia with copper, the heat pump system has been separated from the electrical parts by a brick wall. An emergency ventilating system, which forces eventually escaped ammonia out of the building, is also installed.

Overall performance of the system

The system is in operation since December 1989. After an initial period of optimization, the performance of the heat pump system has been monitored from May 1990 until July 1991. Figure 8 shows the most important data. The COP is between 4 and 5. The lower COP values in the initial period have been improved by further optimizing the system.

Maintenance report of the installed TPL's

Here a list of the recorded events in the history of the two installed TPL's:

- Okt. 89 Commissioning of the compressors (first application of a TPL in an oilfree heat pump system).
- Nov. 89 (200h): Failure of an aluminum gasket in the cylinder head. Replaced by a new gasket of identical material. O-rings of bad manufacturing quality have also been replaced.
- March 90 (2'100h): Failure of the same gasket replaced by a soft iron gasket.
- Aug. 91 (8'078h respectively 8'200h): planned maintenance

Until the 27th of March 92 the compressors have accumulated 11'835 respectively 11'900 running hours. The planned maintenance in August 91 has shown following results:

- Piston and valves were dry, no measurable change in oil level. inside the crankcase.
- 2 needle bearings showed traces of wear. They were replaced.
- No broken valves; preventive replacement.
- Oilscraper showed wear traces; preventive replacement.

CONCLUSION

The waste heat recovery of a hydro-electric powerplant utilizing a heat pump shows to be energy-efficient. Using ammonia as a refrigerant is even possible in a copper rich environment and avoids the risk of ozone depletion.

The simplified design of the TPL compared to standard crosshead compressors showed to be of no disadvantage: An obviously less expensive compressor proved to be oilfree and reliable.

REFERENCES


Fig. 1 Principle of the Labyrinth Seal

Fig. 2 Cross Section of a K-Compressor
Fig. 3 Differences between a Crosshead Type and Trunk Piston Type Labyrinth Compressor

Fig. 4 Working Principle of a Trunk Piston Labyrinth Compressor
Fig. 5 Actual Piston of a Trunk Piston Labyrinth Compressor

Fig. 6 Mechanical Shaft Seal
Fig. 7 TPL in the Hydro-Power Plant of Wettingen

![Graph showing TPL in the Hydro-Power Plant of Wettingen]

Fig. 8 Performance of the Heat Pump System

![Graph showing performance of the heat pump system with bars for Heating Energy and Coefficient of Performance]