The LNG BOG Labyrinth-Piston Compressor with Flexible Capacity Control

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ABSTRACT

The economic transportation of large quantities of Natural Gas from the producer to the customer can be achieved either by use of gas pipeline or, with the gas in a liquefied state, by ship (LNG tanker).

For LNG ship transportation, a cryogenic receiving terminal is required at the port of destination. Huge installations are required for the safe and economic storage and handling of the LNG and the associated boil-off gases created during unloading and storage.

The technical features of these terminals, like those aboard the LNG tankers themselves, are fascinating in terms of both dimensions and the art of engineering.

Movable and remotely controlled connecting arms between jetty and LNG tanker

Safe and environment-conscious handling of the cargo, prevention of leaks, exposure of materials to cryogenic temperatures and bone dry gas, as well as rapid temperature changes, are of high concern to the designers.

Among the rotating equipment used in this field are reciprocating compressors. This paper presents the design features of Labyrinth-Piston Compressors specially designed for:

Recovering LNG boil-off gas vapour in receiving terminals.
Design and material selection of compressor parts exposed to cryogenic temperatures.
Start-up and cool-down procedures with Labyrinth-Piston Compressors.
Flexible capacity control for different flow requirements during ship unloading and storage.
Operating experience and maintenance reports after periods of remarkable running hours.
INTRODUCTION

An LNG boil-off compressor has to cope with a variety of basic physical problems for which a product designed to normal standards would be inadequate. We would like to mention two aspects which are of special interest in this context.

Exposure To Cryogenic Temperatures

LNG at barometric pressure boils off at minus 160°C. This temperature is well below the limit where some of the common engineering materials alter their properties. As an example we mention the loss of ductility of most unalloyed carbon steels within a temperature span from 0°C to about -50°C.

Bone Dry Gas

Natural gas in form of boil-off is virtually free from water vapour as the dew point is as low as -160°C. On the one side it is a matter of experience that moisture in a tribological system is an important parameter. Together with a number of other factors it has a distinct bearing on wear rates under non-lubricated conditions.

Who decides to employ dry-running self-lubricating materials for piston rings must accept their mechanical and thermal constraints under bone dry running conditions. He must consequently set the stroke and speed of his machine in accordance with the gas conditions, so that the wear rate of the sealing- and guiding-elements can be held within acceptable limits. Already the initial choice of the dry-running material is itself subject to error because the designer is faced with a multitude of available types.

He is much more free to optimize the design of individual parts of his compressor when he employs the labyrinth principle with the following main features:

- avoidance of permanent mechanical friction
- ability to use materials with known, easily certifiable qualities
- simple design of the elements exposed to the process gas
DESIGN AND MATERIAL SELECTION OF PISTONS AND CYLINDERS

To a technically-sophisticated client in the Middle East the explanation outlined above proved convincing. He installed a labyrinth-piston compressor for handling LNG boil-off gas in his terminal as far back as 1985. The running time of this machine now approaches 110’000 hrs representing a valuable record of excellent experience in industrial operation.

The process data which had served for the lay-out of this compressor are presented below:

GAS: CH4 (98%) + N2 (2%)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Pressure</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>suction 1st</td>
<td>1.036 bar</td>
<td>-90 to -160 °C</td>
</tr>
<tr>
<td>discharge 1st</td>
<td>5.2 bar</td>
<td>+25 to -53 °C</td>
</tr>
<tr>
<td>suction 2nd</td>
<td>5.2 bar</td>
<td>+25 to -53 °C</td>
</tr>
<tr>
<td>discharge 2nd</td>
<td>13.6 bar</td>
<td>+38 to +102 °C</td>
</tr>
<tr>
<td>suction 3rd</td>
<td>13.6 bar</td>
<td>+38 to +48 °C</td>
</tr>
<tr>
<td>discharge 3rd</td>
<td>23.4 bar</td>
<td>+88 to +160 °C</td>
</tr>
</tbody>
</table>

Material Selection For Cylinders And Pistons

The above data were guidelines for the materials selected for cylinders, labyrinth pistons and other components of the machine.

The absence of tribological restrictions by using labyrinth sealing techniques left complete freedom for the choice of the best suited metals for the key components in each individual stage. For the 1st stage cylinders with exposure to the lowest temperatures this resulted in the choice of GGG Ni35. This is a nodular cast iron containing 35% of Nickel, also known under the trade name of Ni Resist D5. This alloy simultaneously exhibits remarkable ductility at low temperatures and one of the lowest thermal expansion coefficients known in metals. The corresponding pistons were made of Nickel-alloyed cast iron with laminar graphite.
Reference is made to Table 1 from which the outstanding thermal shock behaviour of GGG Ni 35 in relation to other candidate materials can be seen. This is another valuable virtue specially under transient temperature conditions, allowing the compressor to be started directly from ambient temperature without any precooling.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Tensile strength (N/mm²)</th>
<th>Endurance limit (N/mm²)</th>
<th>Young’s modulus (N/mm²)</th>
<th>Thermal expansion coefficient (x10⁻⁶/°C)</th>
<th>Thermal shock stress (N/mm² ΔT = 100°C)</th>
<th>Ratio</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron, GG 18</td>
<td>180</td>
<td>80</td>
<td>85 000</td>
<td>11.70</td>
<td>100</td>
<td>1.25</td>
<td>0.55</td>
</tr>
<tr>
<td>Austenitic Steel, CrNi</td>
<td>460 600</td>
<td>230 : 300</td>
<td>204 000</td>
<td>20</td>
<td>410</td>
<td>1.80</td>
<td>1.40</td>
</tr>
<tr>
<td>GGG NiCr 20, Type D2</td>
<td>430 190</td>
<td>125 000</td>
<td>17.6</td>
<td>220</td>
<td>58</td>
<td>0.32</td>
<td>0.51</td>
</tr>
<tr>
<td>GGG Ni 35, Type D5</td>
<td>410 185</td>
<td>127 000</td>
<td>4.50</td>
<td>58</td>
<td>--------------------------------------</td>
<td>0.32</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 1: Candidate materials for low temperature components. Comparative combined properties.

The less severe temperatures in the 2nd stage allowed the use of ferritic nodular cast iron with good fracture toughness down to -100°C and bronze for the piston. The 3rd stage cylinder consists of normal cast iron grade GG20.
CONTROL OF TEMPERATURE AND DEFORMATION OF THE CRANKCASE

Gas temperatures at the 1st stage inlet valves are so low that energy imparted to the cylinders during gas compression raises their mean temperature to a value still well below that of ambient air. Therefore they do not have cooling jackets. They cool down well below freezing point of the moisture in the natural atmosphere and consequently become covered with a thick layer of ice when the machine is running.

Icing of 1st stage cylinders after continuous operation of approx. 2-3 months

To ensure a good alignment of the path of the labyrinth pistons, cold deformation of the crankcase underneath the 1st stage cylinders had to be prevented. This was achieved by means of a special water jacket which extends along the upper face of the crankcase and acts as a thermal barrier.

Labyrinth-Piston Compressor for LNG boil-off. 4 double acting cylinders, 2 compression stages. Closed gastight crankcase. Suction temperature -160°C.

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INTERNAL AND EXTERNAL LEAKAGE

Consistent with the design of the pistons, labyrinth seals were also used between the double acting cylinders and the distance piece at the upper end of the crankcase.

Internal labyrinth sealing between double acting cylinder and distance piece of crankcase [piston rod sealing].

Each gland has a collector chamber before the lower end of the labyrinths from where the leak gas is internally returned to the suction up-stream of the 1st stage cylinders.

To attain a perfect external tightness of the machine the passage of the crankshaft through the wall of the crankcase was sealed off by a rotating double sided ring seal immersed in oil. Thus, the entire inside of the frame could be integrated into the gas containing system and could be pressurized at will with either natural gas or an inert gas. In the case presented here it was left at suction pressure level and filled with natural gas. The entire machine represents therefore one hermetically closed shell with no gas leakage to the environment.

Gas-tight sealing of crankshaft between crankcase and environment.
### MAINTENANCE REPORT ON A PERIOD OF 110’000 RUNNING HOURS

<table>
<thead>
<tr>
<th>Component</th>
<th>Replacement Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pistons (total of 4)</td>
<td>no replacement whatsoever</td>
</tr>
<tr>
<td>Piston rod seals</td>
<td>1st replacement after 14350 h</td>
</tr>
<tr>
<td></td>
<td>2nd replacement after 36993 h</td>
</tr>
<tr>
<td></td>
<td>3rd replacement after 61790 h</td>
</tr>
<tr>
<td></td>
<td>4th replacement after 83685 h</td>
</tr>
<tr>
<td>Piston rods</td>
<td>no replacement whatsoever</td>
</tr>
<tr>
<td>Crankshaft seal</td>
<td>1st replacement after 14350 h</td>
</tr>
<tr>
<td></td>
<td>2nd replacement after 36993 h</td>
</tr>
<tr>
<td></td>
<td>3rd replacement after 83685 h</td>
</tr>
<tr>
<td>Bearings:</td>
<td></td>
</tr>
<tr>
<td>Piston rods guide bearings</td>
<td>1st replacement after 36993 h</td>
</tr>
<tr>
<td></td>
<td>2nd replacement after 61790 h</td>
</tr>
<tr>
<td>Crossheads</td>
<td>no replacement</td>
</tr>
<tr>
<td>Crosshead pin bearings</td>
<td>no replacement</td>
</tr>
<tr>
<td>Connecting rod bearings</td>
<td>no replacement</td>
</tr>
<tr>
<td>Crankshaft bearings</td>
<td>one bearing lost after 14350 h</td>
</tr>
<tr>
<td></td>
<td>no further replacement</td>
</tr>
</tbody>
</table>

#### Valves

No precise records are available on life-time of valve discs. However, orders for replacement parts indicate an average life-time expectation of a valve plate of 16’000 hrs at least with no distinction as to cold- or warm-running valves. That these results are remarkable will be widely acknowledged.

#### OTHER LNG TERMINALS

The successful performance of the Labyrinth-Piston Compressor in this market segment has encouraged other terminals to install new machines of the same kind built to the same principles.
This picture shows a group of 3 Labyrinth-piston compressors for LNG boil-off in a Taiwanese terminal where LNG is received, stored and evaporated for distribution by a pipeline system throughout the island of Taiwan. The first three identical labyrinth piston compressors were delivered in 1988. When the terminal was extended in 1992, in view of the successful operation of these units an order for an additional compressor was placed. In this case a two stage machine was required. As the discharge temperature after the 2nd stage reaches about minus 50 to 0°C only, both stages have uncooled cylinders. The process data which had served for the lay-out of this compressor are:

<table>
<thead>
<tr>
<th></th>
<th>suction 1st</th>
<th>discharge 1st</th>
<th>suction 2nd</th>
<th>discharge 2nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS: CH4 (98%) + N2 (2%)</td>
<td>1.036 bar -106 to -160 °C</td>
<td>2.9 bar -36 to -97 °C</td>
<td>2.9 bar -33 to -93 °C</td>
<td>6.8 bar -45 to +35 °C</td>
</tr>
</tbody>
</table>

**MAINTENANCE REPORT ON THESE COMPRESSORS**

This report is very short. When the first three compressors had all passed 15,000 running hours. One compressor only was opened up after 10,000 running hours. Piston and bearing clearances, piston rod seals and valves were checked. Some gland rings and some minor valve parts were replaced. The maintenance report ended up with the remark: "like new!"
That means, two machines have never been touched by maintenance people after 2 x 15,000 running hours and there are no signs of abnormality which would easily be seen from registered data.
START-UP PROCEDURE

Special attention has been given to producing a simple start-up procedure. The low thermal expansion coefficient of the chosen cylinder material leads to low thermal stress. Together with carefully designed pulsation dampeners and a well-engineered gas piping arrangement the system allows full automatic start-up of the compressors. The transition from ambient temperature down to boil-off temperature is achieved without any precooling.

![Graph showing temperature readings during start-up of an LNG boil-off gas Labyrinth-Piston Compressor.](image)

Gas temperature readings taken during the start-up of a LNG boil-off gas Labyrinth-Piston Compressor.

CAPACITY CONTROL

There are two main reasons, why compressor regulation is used:
The most prevalent one is to adjust the suction flow to match the process demand.
The second important reason is to save energy.
In contrast to many other compressor types, reciprocating compressors offer a large variety of capacity control systems. The proper type of capacity control is determined by many parameters. Not all types of capacity controls can be used with a given compressor model, a specific pressure range and gas composition. The engineer who has to specify a process compressor, should clearly describe the required turndown requirements and ask the compressor manufacturer to recommend the best applicable type of capacity control.

The compressors in the Taiwanese Terminal are equipped with valve unloaders 100/75/50/0%.

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For two stage compression without gas coolers and reliquefaction of the compressed gas, this is the favorite solution.

The described compressor in the Middle East however, as an alternative to valve unloaders, is equipped with a bypass over the first stage. This system is very common for three stage compression in industrial gas applications. With an intercooler between second and third stage the discharge temperature of the third stage is well under control.

By using the superheating effect of the bypassed gas on the suction temperature of the first stage, the mass flow can be continuously turned down to 50%.

This system has demonstrated:
- simple reliable low cost solution, as standardized components can be used.
- continuous and flexible capacity control with a good partial load efficiency.

PLANT DESIGN

Sulzer Burckhardt, in addition to being a compressor designer and maker also engineers, procures and, if
desired, provides commissioning of whole systems. Complete systems that bear our handwriting include every nut and bolt from suction to discharge side of the compression unit comprising pulsation equipment, filters, lube oil systems, motor driver, gas and water piping, pulsation studies, mechanical- and thermal stress analysis of the gas pipings, as well as complete control systems.

Two other LNG boil-off gas compressors in the design stage commissioned in December 1993 in a Korean LNG receiving terminal.

The maintenance report for the above compressors at Pyeong Taek Korea show very similar satisfactory results. When considering all the seven LNG units mentioned in this paper, comprising 28 pistons, with a total running time of more then 350000 hours, there has been no replacement whatsoever of any labyrinth piston.
This is quite a remarkable operating experience.
CONCLUSION

Low gas temperature challenges gas compressors in two ways:

1. physical contact with cold gas and consequences for material properties
2. absence of humidity (low dew point) with a strong bearing on tribology in non-lubricated areas

The application of labyrinth seals in reciprocating compressors is a logical answer to these problems. Labyrinth piston compressors have demonstrated this in industrial operation successfully down to boil-off temperature of natural gas at minus 160°C. Such machines can be built with zero leakage to the environment.

¥ they need little maintenance
¥ plant operators praise their reliability
¥ maintenance crews enjoy their low attention requirements

Maintenance People love the LABY®.