Commercial Cryocoolers for use in HTS applications

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AFCryo is a joint Venture established in 2017 between Absolut System and Fabrum Solutions to provide large scale cryocooler designs and production
Contents

✓ Introduction – Fabrum Solutions and Absolut System experiences in cooling HTS applications
✓ Looking at industrial applications
✓ Characteristics of an industrial liquefier
✓ **AFCRYO** answer: Diaphragm pressure wave generator liquefier
✓ Summary
- Location Christchurch, New Zealand
- Founded in 2004
- High precision manufacturing processes
- 25 Employees
- 2500 m² Office/WorkShop
Single phase composite cryostats for 3-phases HTS transformer

- 1MVA 3-phases transformer 11kV/240V demonstrator run by IRL (Industrial Research Lab - NZ, now Callaghan Innovation), operated at 65K
- Both High and Low voltage windings used ReBCO conductors with iron core external to the cryogenic region
- Cryostat vacuum space was filled with glass microspheres, and continuously pumped with rotary pump. 60W cryostat losses (without current leads)
- 3 separated cryostats is not optimal for the heat leaks through the bushing (6 for HV and 4 for LV) compared to common cryostat for 3 phases, but it brings a lot of simplicity to the cryostat design and tests
Single phase composite cryostats for 3-phases HTS transformer (cont’d)

- Transformer packed and designed with relocation in mind, making use of 6m long shipment containers (cryosystem container and 3 cryostats container)
- 65K subcooled LN2 cryosystem with natural convective flow refrigeration developed by Absolut System
Composite cryostat for LN2 cooled homopolar motor

- Motor designed using 2G, Roebel cable, carrying 5 kA, operated at 77K, Max shaft speed was 1800rpm
- The inverted mushroom cryostat has a total wall thickness of 21.5mm, including 9.5mm of vacuum insulation space
- The cryostat has a joint line on the perimeter of the mushroom to enable access to the homopolar rotor
- The joint line was designed to withstand direct contact with LN2, and withstand hydraulic pressures
Composite Dewar for AC Loss coil Test Facility

- SuperPower's calorimetric AC loss coil test facility aiming to determine the ac losses developed in prototype winding configurations of 2G HTS conductor architectures
- LN2 based
- Dewar able to handling coils up to 850 mm diameter and 600 mm height and losses from a few watts to up to 1500W
- Optimized for low background heat leak and mitigates any eddy current losses
- Location Grenoble, France
- Founded in 2010
- Engineering and R&D Focus
- 14 Employees
- 700 m² Office/Laboratory
Fully automatized and reliable 65K subcooler for IRL / 3ph HTS transformer

- 1500W cooling power @ 65K is achieved by 3 GM CRYOMECH AL600 cryocoolers connected to LN2 thermosiphon circulation loop (no cryogenic circulator)
- 1 pumped LN2 sub-cooler heat exchanger in back-up of the GM coolers (used in case of failure or during GM cooler maintenance phases)
Fully automatized and reliable 65K subcooler for IRL / 3ph HTS transformer (cont’d)

• Baseline 3*AL600 GM cryorefrigerators are connected via a Thermal Link Assembly (TLA) to the thermosiphon

• Innovative TLA using annular heat pipe to allow thermal coupling and dismounting for maintenance of the cold head with system still in operation with external LN2 supply
Nitrogen recondensing system for ECCOFLOW 3 phases HTS FCL

- 1 CRYOMECH GM AL600 cryocooler (500W/80K) with enhanced heat transfer area at cold tip for LN2 Boil Off re-condensation by natural convection
- Dismountability for cold head maintenance
- System delivered to Air Liquide Advanced Technology
Subcooled forced flow pressurized Nitrogen cryostat for dielectric measures

- Subcooled LN2 forced flow @ 5 bars / 77K
- Dry pumped flow option @ 65K
- 150 kV dielectric measures on isolators used in HTS cable applications performed by ESPCI
- 2 meters height cryostat : SS inner shell, Polyurethane foam, G10 liner designed by ABSOLUT SYSTEM and manufactured by FABRUM
Study of HTS FCL and HVDC breaker

- Double wall LN2 cryostat
- 4 coils (700 kg each) operated at 5bars @ 68K
- 72.5 to 320 kV HV – nominal current 1.5 kA (15 kA peak)
- 13.2 MJ quench power (2 successive quenches at 10 sec)
Remote Helium cooling loop for MgB2 superconducting cable system

• Supercritical 20 bars helium forced flow loop @ 20K
• Helium mass flow rate of 10 g/s
• Cooling source composed of 2 CRYOMECH AL325 GM type cryocoolers
• Noordenwing type cryofan from CRYOZONE is used for the circulation
• Thermal shielding provided with lost LN2 loop forced flow
• **114W @ 20K net cooling power is distributed with 4.4 m flex lines**
Remote Helium cooling loop for MgB2 superconducting cable system (cont’d)

• Piping and Instrumentation Diagram
Remote Helium cooling loop for MgB2 superconducting cable system (cont’d)

• LN2 distribution box for:
  ➢ 7 bars subcooled 77K forced flow loop to the cable thermal shield
  ➢ 1.4 bars pressurized bath for the 20K cooler thermal shield and the cable current leads

• 600L LN2 dewar designed by ABSOLUT SYSTEM & manufactured by FABRUM. G10 inner wall, PU insulating foam and SS external liner
30K Remote Helium cooling loop
- 80W @ 30K with 1 * AL325 GM cryocooler
- Room temperature compressor for the forced flow (and thus counter flow heat exchangers)
- MgB2 based HTS motor for JEUMONT Electric

50K Remote Helium cooling loops
- 43W @ 50K with 1 * AL 230 GM cryocooler
- Cold cryofan
- ISO5 class clean room compatible – 50 dBA
- IR detectors electro-optical characterization for SOFRADIR

Remote Helium cooling loops can be scaled to 65-77K (but limited to few hundreds of Watts)
Market needs for industrial on-site liquefaction

Liquid Nitrogen (LIN) Solutions
- HTS applications for transformers and FCL’s
- Aircraft Tires on the Flight Line
- Wheel & Brake Repair Facility
- Landing Gear Struts
- Recharging Cylinders
- Inert Explosive Vapors within Fuel Tanks
- Emergency Power Unit Purge & Test (F-16)
- Optical Device Enclosures & Dome Lanterns
- High Pressure Missile Tube Recharge
- Industrial gas ‘on-site’ supply

Liquid Oxygen (LOX) Solutions
- Aviation Breathing Oxygen
- Medical Breathing Oxygen
- Welding & Cutting
- Recharging Cylinders
Liquefaction Applications

LNG Marine Delivery
- Reliquefaction of methane boil-off during marine transportation
- Scalability of units
- 3kW to 15kW packages

Liquid Air
- High density (728:1)
- Two times the density of compressed air resulting in extended operating times
- Low operating pressures (70 – 125 PSI)
- Significant safety benefit
- Heat stress mitigation

Cryo Life Support Systems, LLC
Market requirements for Cryocooler Liquefaction Solution

• Low maintenance requirements = long operating periods

• Rapid deployment and re-deployment
  • Containerised and robust for airlift/trucking movements
  • Easy installation/connectivity
  • One push button operation to activate
  • Rapid cooldown cycle < 30 minutes
  • One button shutdown
  • Autonomous operation and infield fault diagnostic functionality

• Elevated net coefficient of performance (total input compressor/cooling power)

• Severe environmental conditions

• Automated load matching of output power

• Tolerant to vertical and angular movements (earthquakes and marine)

• Low-tech onsite servicing
Diaphragm Pressure Wave Generator
an industrial solution

Attributes

Patented diaphragm pressure wave generator delivers rugged, low maintenance and efficient cryocooling

Long life diaphragm separating the cryogenic cold head from the pulsation wave components: no impurities

Off-the-shelf drive mechanisms and components: motors, seals, bearings and controls
Pulse tube cold head

Attributes

In-line mono stage high frequency pulse tube cold head
Simple to design and produce (low cost)
No moving parts – Absolutely NO MAINTENANCE
Ultra high reliability
The metal diaphragm pressure wave generator technology in 2005

1st cryocooler using a Pulse Tube cold head

1st Prototype of 330cc DPWG

1st Prototype of 1000cc DPWG

Commercial manufacture of PTC330 and PTC1000 units

Design of multiple products using Pulse Tube technology
**1st Work Horse product**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Swept Volume</strong></td>
<td>330 cm³</td>
</tr>
<tr>
<td><strong>Power @ 77K</strong></td>
<td>480 W</td>
</tr>
<tr>
<td><strong>No Load Temperature</strong></td>
<td>45K</td>
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<tr>
<td><strong>Motor Power @ 77K</strong></td>
<td>12 kW</td>
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<tr>
<td><strong>Weight</strong></td>
<td>800 kg</td>
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<tr>
<td><strong>Dimensions (m)</strong></td>
<td>1.9(L)x0.8(W)x1.7(H)</td>
</tr>
</tbody>
</table>
PTC1000

Swept Volume 1000cm³
Power @ 77K 1450W
No Load Temperature 43K
Motor Power @ 77K 25kW
Weight 1300kg
Dimensions (m) 1.8(L)x1.2(W)x2.2(H)
Liquefaction System with Diaphragm Cryocooler

- Gas supply from PSA, ASU or bulk supply (1 – 30 bar)
- Condenser liquefies the gas which is stored in the pressurised dewar
- The cryocooler is effective over a large temperature range
Loading

Cooling loads are not constant. In order to match the load we undertook development to vary the cooling power at a given temperature.

Two approaches:
1. **Frequency modulation.** This varies the cooling power by detuning from the optimum Pulse Tube frequency. However, the input power remained constant. This was undesirable due to loss of efficiency.
2. **Pressure tuning.** The helium pressure was varied over several runs. The cooling power and input power requirements reduced at lower pressure giving consistent system efficiency. The relationship between cooling power, helium pressure and motor power is shown for our PTC330 the figure.
Cryocooler Technology

Our PTC1000 cryocooler employs three pulse tubes mounted to one Pressure Wave Generator (PWG).

Due to this configuration, we are able to pre-cool the incoming gas with one pulse tube, leaving the remaining two to do the liquefaction.

This presents a distinct advantage that heat is being removed at a higher temperature, where our cooling power is elevated.

We have shown an increase in liquefaction rate of 20% over parallel configurations.
LGU 350
350 l/day LN2
27 kW

LGU 700

LGU 1000

Development of units to meet market requirements

- Progressed technology up to 15 liters of LN2 per hour per cryocooler (PTC1000) at 77K/1bar
- Quick start up, Liquid production in <15 min.
- Modular configurations to meet customer requirements are trivial
- Tolerant of shock associated with transportation
- Palletised/containerised for ease of lifting and transportation
- Very simple on site servicing - No clean environment nor specialist & tools required

Summary

LGU 350
350 l/day LN2
27 kW

LGU 700

LGU 1000