Ongoing R&D activities for ATLAS and CMS phase 2 upgrade CO₂ cooling systems

https://indico.cern.ch/event/775863/contributions/3413654/

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Bart Verlaat, CERN

On behalf of the CERN CO₂ cooling team and LPSC-Grenoble
Future challenges in CO$_2$ cooling

- The phase 2 upgrade of CMS and ATLAS has interesting challenges for the CO$_2$ cooling developments
  - Colder cooling temperature inside the detectors (~-40°C)
  - Much larger system (60x CMS pixel, 150x ATLAS IBL)
  - Reduction of CO$_2$ fluid stored underground
  - Simulation R&D to predict increased dynamic behaviour
  - Going green for the primary => the entire cooling uses only natural refrigerants
  - Severe height differences resulting in larger system losses
    - Vertical transfer lines
    - CO$_2$ primary on the surface

- The different development lines have all dedicated R&D projects with EP-DT
We reach the cold practical limit of CO₂

Need to go colder for future detectors? See talk this afternoon “R&D for a colder future in HEP”
https://indico.cern.ch/event/775863/contributions/3413707/

ATLAS example

Temperature

- Sub cooling
- Heat exchange
- CO₂ freezing point (-56°C)
- CO₂ pressure drop (°C/bar)
- Temperature loss increase at lower pressures
- Temperature loss over pressure drop (°C/bar)
- Cooling Temperature (°C)
- Transfer line length

Detector cooling target temperature (-35°C)

Temperature

1. Plant saturation: -45°C
2. dT transfer line: 2°C => -43°C
3. dT flexline: 3°C => -40°C
4. dT detector: 5°C => -35°C
5. Heat transfer gradients must be included in local support design

- Temperature gradient budget
- The temperatures are on the limit, not much margin
- High pressure makes CO₂ an effective cooling fluid, advantages gets less effective at lower temperatures.
- The heat transfer also gets worse at lower temperature

See Paolo’s slides yesterday:
Baby-DEMO experimental set-up to study 2PACL low temperature operation

- Insufficient cooling due to low superheating
- Manual control of chiller: -50°C cooling achieved
- Automatic control returned

Diagram showing temperature and pressure changes with annotations:
- Pump recovery after cavitation
- Insufficient cooling due to low superheating
- Manual control of chiller
- Automatic control returned
Scaling up the cooling system

The DEMO plant is a 33/67/100 kW cooling plant (130kW for CMS calorimeters)

CMS: 8 plants, 21 heads, 534 kW
ATLAS: 7 plants, 13 heads, 300kW
Influence of the accumulator size to the system

The system volume scaled linear with the cooling power (same flow speeds)

- **Temperature profile**
  - Simulation of a 70 kW heatload switch on at $T_{sp}=30^\circ C$
  - $V_{THL}=350(l), V_{AC}=1050(l), MF=700(g/s), V_{Q_{THL}}=0, L_{AC}=10(\%)$

- **Accumulator level and VQ**
  - Simulation of a 70 kW heatload switch on
  - $V_{THL}=350(l), V_{AC}=1050(l), MF=700(g/s), V_{Q_{THL}}=0, L_{AC}=10(\%)$

- **Cycle in PH diagram**
  - Simulation of a 70 kW heatload switch on at $T_{sp}=30^\circ C$
  - $V_{THL}=350(l), V_{AC}=1050(l), MF=700(g/s), V_{Q_{THL}}=0, L_{AC}=10(\%)$
System volumes (status SPR November 2018)

Volume reductions are ongoing

- A traditional 1:3 accu would lead to very large CO₂ quantities underground
- How small can we make the accumulator? Where is the limit?

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19/06/2019
How large can a reduced accumulator be?

Simulation of a 80 kW heatload switch on

\[ V_{\text{TFL}} = 300(\text{l}), V_{\text{AC}} = 330(\text{l}), MF = 800(\text{g/s}), VQ_{\text{TFL}} = 0, L_{\text{AC}} = 5 \, \% \]

From 5\% to 95\%

110\% accumulator

Exchanged fluid

mass 2.5x mass flow

Simulation of a 80 kW heatload switch on at Tsp=40°C

\[ V_{\text{TFL}} = 300(\text{l}), V_{\text{AC}} = 330(\text{l}), MF = 800(\text{g/s}), VQ_{\text{TFL}} = 0, L_{\text{AC}} = 5 \, \% \]

Density change as a function of start VQ and Tsat in transfer line at a VQ increase of 0.3

- Tsat=50°C
- Tsat=40°C
- Tsat=30°C
- Tsat=20°C
- Tsat=10°C
- Tsat=0°C
- Tsat=10°C

½ the density to accumulate = half accumulator size needed

Pre-vaporizing to 5\% necessary in a manifold heater when using a 50\% accumulator

50\% accumulator with 5\% pre-vaporization

110\% accumulator
**Accumulator reduction summary**

- **Summary of the simulations:**
  - >110% accumulator to catch detector load from liquid filling
  - >50% accumulator to catch detector load from a 5% pre-vaporizing

- **Target idea for system sizing:**
  - ~100% accumulator with pre vaporization in the system
  - Pre vaporization can be achieved by:
    - Ambient pickup
    - Warm nose heating (ATLAS)
    - Pre-heaters (CMS)
    - Warm gas mixing
  - Pre vaporization can be switched off when detector is on when added extra

- **Surface storage**
  - When the accumulators reaches level thresholds, the fluid is exchanged with a common surface supply

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19/06/2019

2PACL concept with surface storage  
B. Verlaat

Normal 2PACL concept
Baby-DEMO upgrade for Surface Storage testing

Small accumulator cabinet
Stephane Latil, LPSC
• The new system will be much more dynamic
• Development of a simulation platform to investigate plant behavior
• Validated against CORA for normal 2PACL cycle
• Will be verified with Baby-DEMO for surface storage simulations
• Future → Virtual commissioning setup for operator training
ATLAS & CMS Ph2 upgrade cooling using only natural refrigerants

- **Water cooling tower**
  - Water temperature: 27°C
  - Coolant temperature: Down to -55°C

- **Experimental Cavern**
  - CO2 temperature: +15/-20°C
  - Refrigerated low pressure surface storage of CO2
  - Temperature: Down to -35°C

- **Service Cavern**
  - CO2 temperature: +15/-45°C
  - Refrigerated low pressure surface storage of CO2
  - Temperature: Down to -35°C

- **Multiple 2PACL’s with reduced accumulator**
  - CO2 primary temperature: Trans critical CO2 primary
  - CO2 back-up temperature: Up to 100°C

- **Air cooled & low power back-up CO2 chiller**
  - Temperature: +15 to -45°C

- **+ Dry-air and vacuum systems**
R744 primary cooling a reborn green technology

- Due to high pressure, the system can bridge the depth of the access shaft
  - System can be installed on surface, evaporators underground
  - No intermediate brine is needed
- Primary cooling in 50kW slices
  - Slice activation based on capacity request
  - Slices give redundancy and maintenance access
  - Back-up cooling integrated by integrated air-cooling (1 slice on UPS)

R744, a new and old technology!
The system is trans-critical, what does it mean?

**Trans-critical vs sub-critical**

A trans critical cycle can reject its heat to much higher temperatures: **air-cooling**
Primary R744 (CO₂) cooling cycle: A trans-critical cycle

- A special design to work near the triple point with high suction pressure stability (Stable evaporator temperature, See slide 4)
- A prototype for DEMO is in the final purchase stage
  - A 100 kW two slice concept (Slice enabling control testing)
- Concept development together with the NTNU experts (Trondheim, Norway) and EN-CV.
  - NTNU was responsible for the revival of CO₂ back in 1995
ATLAS and CMS cooling vertical height challenges

ATLAS and CMS CO₂ cooling: same concept, same hardware & different distribution

Compared to previous built systems, we have serious height differences in the transfer lines

- 80m height for primary R744 system
- Up 20m height difference in 2-phase transfer lines

ATLAS transfer lines are nearly horizontal
R&D: Vertical flow research (1)

- Small scale research to understand theoretical aspects
  - 8mm ID tube
  - Flow 16 g/s
  - Flow visualisation
  - Accurate measurements of thermal and pressure profile
  - Includes horizontal section to compare better understood vertical flow.

- Sensor calibration in progress
- 1st results expected soon
Current CMS pixel is extracted and replaced with dummy loads.
Extra sensors installed
Study of vertical flow inside the existing concentric transfer lines.

The dummy load for DEMO is connected by a full scale vertical transfer line.

153 COOLING LAB
8x15Kw=120kW
Dummy load
CMS full scale transfer line section
Conclusions

• Many new developments are needed for the next generation large CO₂ cooling plants

• Many research programs are on going in EP-DT

• All research is combined around the DEMO and Baby-DEMO programs

• Primary cooling will be also CO₂ (R744), making the cooling to work with only natural refrigerants

1st step to a green cooling future at CERN
• The CO2 cooling systems for the phase-2 upgrade of ATLAS and CMS are an order of magnitude larger in cooling power than the CO2 cooling systems developed so far. This enlargement of the systems brings new engineering challenges which are currently being studied in several R&D programs in the CERN EP-DT-FS cooling team. A prototype cooling unit, called DEMO, of about 100 kW is being built.

A proportional enlargement of the system would lead to very large CO2 accumulators and hence large CO2 quantities stored underground. In order to reduce the volumes, a modified control concept is under study to supply the multiple plants with a common CO2 storage on the surface. A modified control mechanism to fill and empty the system is foreseen.

The enlargement of the systems also leads to large diameter transfer lines between the cooling plants in the service caverns and the cooling loops in the detector. These transfer lines typically have 2-phase flows in both horizontal and vertical orientation. The behaviour of 2-phase CO2 flow under these novel conditions is insufficiently understood and is therefore subject to a dedicated R&D program. In the CERN cooling laboratory in B153 a set-up of 8mm ID pipes is mounted in order to understand the fundamental behaviour of 2-phase flow especially in vertical pipes. Transparent sections are present for visualization of flow patterns. Following the small-scale setup, a next R&D on a real size transfer lines up to 2″ will follow using the large capacity DEMO cooling plant, while smaller scale transfer lines, with the typical size of the detector to manifold ones are being tested in real scale on the CMS experiment for vertical flow effects.

A second large R&D activity is the application of CO2 as working fluid also in the primary cooling system. When used as primary cooling fluid, CO2 is referred to as R744, the refrigeration code. A R744 primary system is able to cool the underground CO2 plants directly to the air or the primary water towers on the surface. This application makes the full detector cooling to work with natural refrigerants only, ensuring a green future for the next generation cooling systems at CERN. The primary R744 cooling R&D is done in a successful collaboration between world experts from NTNU in Norway and EP-DT and EN-CV at CERN.