SYSTEM DESIGN CHALLENGES FOR CO₂ EVAPORATIVE COOLING IN TRACKING DETECTORS

P. Tropea - CERN EP-DT
OUTLINE

This is not a talk about ALL advanced cooling techniques

(Vertex2017, P. Petagna)

This is not a “publicity” talk about CO$_2$

(Vertex2011, H. Postema)

... but rather a collection of experiences & possible guidelines to get to a properly working CO$_2$ system

- Brief introduction to CO$_2$ cooling: the 2-PACL cycle
- The challenges in design phase
- Operational aspects
- Conclusions
WHERE?

So far...

LHCb Velo 1.6 kW @ -25 C

ATLAS IBL 1.5 kW @ -35 C

AMS Tracker 150 W @ -20 C

CMS Pix Phase I upgrade 7 kW @ -25 C

In the near future ...

LHCb Velo Upgrade - 2 kW @ -35 C


CBM STS


BELLE II Vertex Detector

Source: H. Ye “Thermal Test and Monitoring of the Belle II Vertex Detector” Forum on Tracking Detector Mechanics 2016, Bonn

AMS Tracker 150 W @ -20 C
AND THEN? AT HL-LHC…

CMS

<table>
<thead>
<tr>
<th>Detector</th>
<th>Evaporation T at the detector exit</th>
<th>Heat load of detector</th>
<th>Ambient pick up</th>
<th>Total heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Tracker</td>
<td>-35</td>
<td>102</td>
<td>11</td>
<td>113</td>
</tr>
<tr>
<td>Inner Tracker</td>
<td>-35</td>
<td>50</td>
<td>5</td>
<td>55</td>
</tr>
<tr>
<td>Barrel Timing Layer</td>
<td>-35</td>
<td>45</td>
<td>6.5</td>
<td>52</td>
</tr>
<tr>
<td>Calorimeter Endcap</td>
<td>-35</td>
<td>240</td>
<td>7</td>
<td>247</td>
</tr>
<tr>
<td>Endcap Timing Layer</td>
<td>-35</td>
<td>80</td>
<td>8.0</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>517</td>
<td>37.5</td>
<td>555</td>
</tr>
</tbody>
</table>

ATLAS

<table>
<thead>
<tr>
<th>Detector</th>
<th>Evaporation T at the detector exit</th>
<th>Heat load of detector</th>
<th>Ambient pick up</th>
<th>Total heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Endcap</td>
<td>-30</td>
<td>26.2</td>
<td>2.6</td>
<td>113</td>
</tr>
<tr>
<td>Pixel Barrel</td>
<td>-35</td>
<td>55.1</td>
<td>5.5</td>
<td>60.61</td>
</tr>
<tr>
<td>Pixel Insertable</td>
<td>-45</td>
<td>20.6</td>
<td>2.1</td>
<td>23</td>
</tr>
<tr>
<td>Strip</td>
<td>-30</td>
<td>122.7</td>
<td>12.3</td>
<td>135</td>
</tr>
<tr>
<td>HGDT</td>
<td>-30</td>
<td>25</td>
<td>2.5</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>249.6</td>
<td>24.96</td>
<td>359</td>
</tr>
</tbody>
</table>

A good order of magnitude bigger & more complex than ever…
11-1: Subcooled liquid CO$_2$ is circulated using a membrane pump. 1-3: Cold refrigerant passes through an internal heat exchanger where it exchanges heat with the return fluid and gets heated to the evaporator temperature. 3-5: adiabatic + diabatic expansion. 5-6: Saturated liquid now enters the evaporator where it cools the detectors. 8-9: The return line forms the internal heat exchanger, and heats up the cold supply-side refrigerant to the evaporator temperature. 9-11: The absorbed heat is dumped into the primary external chiller system (conventional vapour compression system) in the condenser, and subcooled liquid CO$_2$ is fed back to the pump.

The **accumulator** sets the evaporator pressure (5 to 9) and thus the evaporation temperature: it is the **system controller**.
The complexity of an evaporative system: each design modification on a components would influence the behaviour of the full system: how?

Thermal contact not treated in this talk
See next talk from Georg + references at the end of this presentation
Detector requirements: **power** & **inlet temperature** are not enough

**The temperature**

The system controls T in 9, i.e. in order to specify the T of evaporation inside the detector, one need to know the Δp across the detector (5-6) & the return pipes (6-7,8)+ transfer lines (8-9) : in 2-phase, Δp= ΔT

Specs to system design:
- T @ accumulator
- Δp from 5 to 9: detector & all return lines

**CO₂ operational limits: -47°C @ accumulator**

1) DETECTOR EVAPORATOR DESIGN

2) TRANSFER LINE DESIGN

Need reliable models to predict Δp & Heat transfer coefficient (HTC) in boiling CO₂
**THE CO$_2$ 2-PHASE FLOW DP & HTC MODELS**

Frictional pressure drop (I) & HTC (II) prediction based on flow pattern maps

CO$_2$ two-phase pressure drops prediction methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Percentage of Predicted Points within ±30%</th>
<th>Mean Error</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chisholm (1973)</td>
<td>56.1%</td>
<td>66.8%</td>
<td>73.8%</td>
</tr>
<tr>
<td>Friedel (1979)</td>
<td>71.1%</td>
<td>30.9%</td>
<td>55.8%</td>
</tr>
<tr>
<td>Grönerud (1972)</td>
<td>30.2%</td>
<td>75%</td>
<td>113.1%</td>
</tr>
<tr>
<td>Müller-Steinhagen and Heck (1986)</td>
<td>55.8%</td>
<td>33.3%</td>
<td>44.3%</td>
</tr>
<tr>
<td>Modified Chisholm by Yoon et al. (2004)</td>
<td>47%</td>
<td>34.7%</td>
<td>93.7%</td>
</tr>
<tr>
<td>Moreno Quiben and Thome (2007a, 2007b)</td>
<td>42.4%</td>
<td>50.1%</td>
<td>90.6%</td>
</tr>
<tr>
<td>Cheng et al. (2008a)</td>
<td>74.7%</td>
<td>28.6%</td>
<td>44.3%</td>
</tr>
</tbody>
</table>

Any calculation needs proper testing!


Vertica pipe

Horizontal pipe

Cheng - CO$_2$ flow pattern map (2008)
1) Low mass -> small pipe diameter, small wall thickness

2) Enhanced heat transfer coefficient -> small pipes!

**BUT...**

$\Delta T$ along detector increase with pressure drops ($\Delta p$) and reduced pipe diameter

The pipe size needs to be determined optimizing the combined $\Delta T(\Delta p+HTC)$

**TESTING OF THE CHosen GEOMETRY IS MANDATORY to DEFINE REAL PRESSURE DROPS**
1. Ensure saturated conditions at the detector inlet (temperature control & stability): **concentric**

2. Transfer cold fluid with no impact on the rest of the experiment in a reliable way: **vacuum insulated**

3. Limits the pressure drops in order to reduce as much as possible the DT between the detector exit and the regulation accumulator: **proper sizing**
Understanding the effect of gravity on return lines pressure drops: what is the contribution?

2 setups being prepared – controlled lab conditions in CERN EP-DT & real scale CMS during LS2 (T. Pakulski)
The power & the mass flow rate
Power capacity for a given mass flow varies @ different T
“Warm” operation to be well defined in scope in design phase: checkout? Annealing? Detector on/off?

Ex: detector power = 165 kW @ -45C

<table>
<thead>
<tr>
<th>Design VQ</th>
<th>Required Coolant Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>33%</td>
<td>1.51 kg/s</td>
</tr>
<tr>
<td>42%</td>
<td>1.19 kg/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coolant Flow</th>
<th>Resulting Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.51 kg/s</td>
<td>58.8%</td>
</tr>
<tr>
<td>1.19 kg/s</td>
<td>75.7%</td>
</tr>
</tbody>
</table>

1.19 kg/s, X = 60% - >127 kW cooling capacity @ 15C
AND THEN?

Power & temperature requirements are defined, can be sent as input to plant design!

…but what else is missing to have a complete specification set?

1. Make sure evaporation happens in the good place
2. Balancing of parallel loops
3. Think about operation
ONSET OF EVAPORATION & SUPERHEATED LIQUID ISSUES

HTC dramatically change between liquid and two-phase, thus the need to make sure that evaporation starts at the active detector inlet.

1) Make sure that liquid is not subcooled
2) Make sure that no liquid superheating happens

Liquid superheating = Heating of a substance above the temperature at which a change of state would ordinarily take place without such a change of state occurring, for example, the heating of a liquid above its boiling point without boiling taking place; this results in a metastable state.

Two approaches under study:
- pre-heaters (CMS)
- “warm nose” (ATLAS)
Preheater concept tested
(2x10W resistors clamped to pipe)

"give a kick" to evaporation with a high heat flux load at the detector entrance

"Courtes of T. French CERN EP-CMIX"
PREHEATER TESTING

Further development:
- Verification of behaviour at different operating T, with detector power cycles
- Strategy on powering scheme to be validated
- Full detector sub-structure model mock-up

Courtesy of T. French CERN EP-CMX & G. Baldinelli, University of Perugia, IT

Warm Nose Solution

Dp verification done & prototypes produces
Further development:
- Full verification of concept on CO₂ setup

B. Verlaat, CERN EP-DT

C. Rossi, INFN Genova
BALANCING PARALLEL LOOPS (1)

Why? Parallel loops share the same pressure drop & the mass flow in each loop shall be tuned to the specific loop power & geometrical characteristics in order to properly function.

\[ \Sigma m_{di} = m_{TL} \]
BALANCING PARALLEL LOOPS (1)

Why? Parallel loops share the same pressure drop & the mass flow in each loop shall be tuned to the specific loop power & geometrical characteristics in order to properly function.

Typical hydraulic circuit balancing works…but:

\[ \sum m_{di} = m_{TL} \]
BALANCING PARALLEL LOOPS (1)

Why? Parallel loops share the same pressure drop & the mass flow in each loop shall be tuned to the specific loop power & geometrical characteristics in order to properly function.

Typical hydraulic circuit balancing works…but:

1. Manifolding is typically in non accessible areas
2. Pressure drops in the evaporator change dramatically when in liquid or two phase (power on-off)

Introduce fixed pressure drop on liquid phase which is predominant with respect to detector one

- Small object
- Totally passive

Capillaries or calibrated orifices

Δp vs Vapor quality for a sample evaporator
ID 2mm, 3.4m long, massflow 1.2 g/s, power 0-200 W
The tool for parallel loop calculations, based on empirical correlations for \( \Delta p \) in two-phase. Results of a simulation with 8 parallel loops of CMS TB2S.
ORIFICE SOLUTION

1/8 INCH VCR GASKET (6 mm)
250 μm hole

+ Super for small places, just one connector

- Attention: proper filtering to be put in place, typical hole sizes ½ of capillaries ID

NOT FOR NON ACCESSIBLE AREAS

S. Coelli, “Calibrated orifices for CO₂ cooled detectors”, Forum on Tracking Detector Mechanics, Valencia, 2018
CAPILLARIES

- Can typically have “big” diameters (>0.4 mm less risk of clogging)
- Can be used as standard pipes and be routed along detector volume (ex bulkhead to CMS Outer tracker in present design)
- Need calibration (mostly to take into account real pipe rugosity)
A complex and advanced design: Si microchannels

Courtesy of the LHCb VELO group
**OPERATION**

**Cooling rate:** determines the size of plant/primary

**Warming rate:** ATTENTION - EVAPORATIVE SYSTEM CANNOT BE USED TO WARM UP THE DETECTOR VOLUME if no power applied

**Redundancy:** same $\Delta p$ for all detectors fed by same plant, common backup or not? Need to operate cold during maintenance periods/power cuts/shut-downs

**Diagram:**
- Spare plant runs cold over the spare manifold for direct kick-in (IBL method)
- Spare plant replaces any of the other units, which can be dismounted for maintenance or repair
Ad-hoc temperature monitoring needed to assess the system behaviour: info at the level of the plant are not enough!

See:

- Evaporation onset on IBL – K. Sliwa, Forum on Tracking Detector Mechanics 2017

- CMS Pix recent flow tuning operations (private comm.)

For plant operation: a temperature value of the detector is needed at startup to avoid any thermal shock, should be available also when detector is OFF
**GOLDEN RULES SUMMARY**

*Design Temperature*: Si sensor \( T - \Delta T(\text{Thermal contact}) - \Delta T(\Delta p \text{ across detector evaporator}) - \Delta T(\Delta p \text{ across return transfer lines (frictional and static)}) = \text{Accumulator set point: must be achievable! -47 °C is the min so far...}*

*Power dissipation*: The optimum design for the cooling system needs a tuning to a certain flow rate (transfer lines & \( \Delta p \), hydraulic component size, etc) – Flow rate & vapor quality (the margin to overheating in the detector) determine cooling power = \( f(T) \). An optimised system for -35 °C will not provide full cooling power @ +15 °C with the same safety margin to dryout.

*Design of on-detector evaporators*: Find the optimum pipe size looking at the best compromise between material budget and DT (DP+HTC), define operation scenarios to do calculations! **TEST all that you size**
Include studies on evaporation onset (and a monitoring system that allows you to detect if something is going wrong)

*Operation of parallel circuits*: Make your choice of balancing system and make sure you have margin with respect to all operational cases (included running with other subsystems).

*Prepare for operation*: choice of backup method, design for proper monitoring system, communication between plant & detector of relevant parameters (a mandatory one = “detector temperature”).

*On-detector design & operation teams + cooling teams*
CONCLUSIONS

The size of CO$_2$ cooling systems for the next generation of detectors (up to >100 kW per system) makes the design & construction challenge bigger than in any evaporative CO$_2$ system developed so far for HEP.

Several parallel loops from multiple subdetector will need to be operated in parallel & the design of all of them need to be “synchronised”.

A comprehensive approach shall be adopted, where detector design, integration, operation & cooling team must exchange information: the design of each part of the CO$_2$ system strongly influences the rest – ITERATION to converge to an optimized solution is mandatory.

The common development for both ATLAS & CMS allows for intrinsic easier exchange of experience, but the challenge remains!
WHY CO$_2$?

- **Significant saving of cooling hardware** (material budget) into the detector due to the physical properties:
  - large latent heat of evaporation
  - low liquid viscosity
  - high heat transfer coefficient
  - high thermal stability due to the high pressure
- **Very practical fluid to work** (environmental friendly, not activated)
- **Practical range of the detector application** -45$^\circ$C to +25$^\circ$C

Models used: HTC-Kandlikar and dP-Friedel
Volumetric heat transfer is also a good method to compare different fluids.

- How can we put as much heat into a small as possible cooling tube??

![Graph showing heat transfer conduction vs. tube diameter for different fluids.](image)

**Overall volumetric heat transfer conduction**

$L=3 \text{ m, } Q=400 \text{ W, } T=-20 ^\circ \text{C, } VQ=0.35$

**Heat transfer conduction**

$L=3 \text{ m, } Q=400 \text{ W, } T=-20 ^\circ \text{C, } VQ=0.35$

Models used: HTC-Kandlikar and dP-Friedel

Cooling & Structure Optimization

Great attention to early design and integration of optimized support structures and thermal management solutions is mandatory for the present and the coming generation of Vertex detectors: not surprisingly all “classes of approach” are represented!

Figure 2: Photograph of the NA62 cooling plate [1] (a), photograph of a prototype structure for the ALICE-ITS [10] (b), X-ray image of the high-impedance, restricted-width structures where the liquid CO₂ evaporates in the LHCb VELO cold plate [7] (c), electron microscopy image of the broadening channels produced by CNM [11] (d), X-ray images of the structures integrated in detector-grade silicon by HLL [12] (e,f).

P. Petagna, Vertex207

ABOUT ON-DETECTOR THERMAL CONTACTS

ABSTRACT PERFORMANCE OF CO₂ COOLING SYSTEMS


ABOUT PIPES & CONNECTORS

Workshop on pipe joining techniques for the ATLAS & CMS Tracker Upgrades

https://indico.cern.ch/event/721360/timetable/#20180518