Calibrated orifices for CO$_2$ cooled detectors

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Working for LHCb UT and ATLAS ITk Endcap Collaborations
SUMMARY

• ISSUES USING EVAPORATIVE COOLING

• COOLING SYSTEM DESIGN
  IMPLEMENTING ORIFICES AS FLOW RESTRICTORS

• ORIFICES CHARACTERIZATION
  EXPERIMENTAL MEASUREMENTS WITH CO$_2$

• PROS AND CONS
INTRODUCTION

Focus on Silicon particle trackers

Detector dissipate power:

• main contribution: Front-End electronics

• The Sensors dissipation increase toward the end of life, in high-radiation environment, near interaction point

To survive ‘thermal run-away’:

• thermal power has to be extracted

• sensor temperature has to be maintained low, i.e. under -5 °C
Several trackers have a **cooling channel integrated** into the local support for the sensors

**DETECTOR COOLING USING BOILING FLUIDS**

- **LHCb UT stave**
- **ATLAS ITk ENDCAP Half-ring**

**CO₂ BOILING IN THE CHANNEL AT TEMPERATURES IN THE RANGE -20 °C ...-40 °C**

**BENEFITS:**

- **Good heat transfer efficiency**
  - => smaller flow-rate needed => smaller diameter => Less material => higher radiation length

- **Nearly uniform temperature**
  - Saturation temperature drops slowly along the cooling channel in relation to the fluid pressure drop
High pressure system
Max Design Pressure > 80 bar
(i.e. rupture disk installed dictates 130 bar)

Risk of thermal-hydraulic instabilities
When the detector has parallel evaporator channels
the circuit design is very important to ensure a margin against uneven flow distribution

Risk of dry-out
If the cooling flow-rate decreases in an evaporating channel
=> detector damage
PARALLEL BOILING CHANNELS

For parallel evaporators connected to common headers:

- **Hydraulic resistance at the inlet improves stability:**
  System less sensible to the pressure drop variations of the two-phase region

  ⇒ The cooling distribution has to implement INLET HYDRAULIC RESISTANCE that should **induce a pressure drop 5 ... 10 times bigger than the EVAPORATORS pressure drop** in nominal operation

- **Hydraulic resistance at the evaporator outlet is detrimental**
  => avoid exhaust flow cross-section restrictions
boiling cooling system with parallel channels

Add inlet hydraulic resistance

Technical choice between:
- Distributed pressure drop => capillary pipes
- Local pressure drop => flow restrictors

Evaporator characterization => to set the required inlet geometry

Experimental set-up
to test and validate the design
COOLING SYSTEM DESIGN
IMPLEMENTING ORIFICES
AS FLOW RESTRICTORS
LHCb UT TRACKER

Total cooling power ~ 4 kW

CO$_2$ evaporating in 68 parallel ‘serpentes’

EVAPORATORS Thermal-hydraulic characterization

Analytical calculations difficult when no correlations are available for peculiar design typologies

=> Experimental investigation:
• measurements on 1:1 prototypes
• Full power with dummy heaters
• TRACI 2-Phase Controlled Pressure cooling unit
UT DETECTOR PARALLEL EVAPORATORS

UT is made of 8 similar units

Differences between parallel evaporators:

- pipe in the central stave:
  - Longer
  - More bends

- thermal load:
  - Central sta 50% more power than lateral staves

Central stave measured pressure drop at working point is around 350 mbar

⇒ design pressure drop for the inlet restrictors = 3 bar
**UT CO₂ DISTRIBUTION SYSTEM**

**CALIBRATED ORIFICES are used as inlet flow restrictor**
Advantages:
- **space saving** in a crowded area
- **no need for 68 capillaries** and additional joints

*Laser orifices on VCR blind gaskets*

WARNING: install the flow restrictors on the correct side (the inlet)!

LHCb UT manifold are outside the detector active area

=> Possible to use Swagelok Stainless Steel components

**VCR connections are used in the assembly**

Manifolding and connection piping
ORIFICES
CHARACTERIZATION
EXPERIMENTAL
MEASUREMENTS WITH CO$_2$
CHARACTERIZATION OF FLOW RESTRICTORS WITH CO$_2$

Experimental measurement of the hydraulic resistance to be mounted at the inlet

Investigations are in progress in Milano: capillary and orifices pressure drop and temperature drop

\[ \text{PT} = \text{Fluid Pressure transmitters} \]
\[ \text{PT} = \text{Fluid Temperature transmitter} \]

\[ \text{Tube internal diameter} = 4,6 \text{ mm} \]

The actual work is dedicated to both the LHCb UT tracker and the ATLAS ITk Pixel Encap, but the measurements and outcomes can be useful for any CO2 cooled system
TEST CIRCUIT FOR THE CO2 TEST

- COLD-BOX WITH ARMAFLEX INSULATION
- CO₂ COOLING SUPPLY FROM TRACI COOLING UNIT WITH CO₂ MASS FLOW-RATE MEASUREMENT
- CO₂ PRESSURE AND TEMPERATURE TRANSMITTERS BEFORE/AFTER THE COMPONENT UNDER INVESTIGATION

Flow restrictors tested:
- 200 micron (0.008’’) Laser orifice in VCR gasket
- 250 micron (0.010’’) Swagelok flow restrictor
- 305 micron (0.012’’) Swagelok flow restrictor
- 380 micron (0.015’’) Swagelok flow restrictor.
FLOW RESTRICTORS FOR THE CO₂ COOLING TEST

SWAGELOK ¼ INCH FLOW RESTRICTOR

FROM CATALOGUE:
6LV-4-VCR-6-DM-010P, 6LV-4-VCR-6-DM-012P, 6LV-4-VCR-6-DM-015P, 6LV-4-VCR-6-DM-017P

LASER HOLE IN VCR GASKET

CUSTOM ORIFICES:
200, 225, 250, 275 μm
OTHER GEOMETRICAL CHARACTERISTICS USABLE FOR THE PRESSURE DROP CALCULATION IS LENGTH \( l = 0.2 \text{ mm} \)

Hole: 0,250 mm (= 250 μm)
Prediction formulas found in the “IDELCHIK HANDBOOK OF HYDRAULIC RESISTANCE” for the ‘THICK-EDGED ORIFICE’ model. We are outside range of validity in many cases.

### SPREADSHEET FOR ORIFICE PRESSURE DROP CALCULATION

<table>
<thead>
<tr>
<th>Geometrical parameters</th>
<th>CO₂ physical properties</th>
<th>Flow parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>d, orifice diameter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>305 micron</td>
<td>0.305 mm</td>
<td>0.000305 m</td>
</tr>
<tr>
<td>D</td>
<td>4.6 mm</td>
<td>0.0046 m</td>
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<tr>
<td>F₀</td>
<td>A=(π*φ^2)/4</td>
<td>7.30246E-08 m^2</td>
</tr>
<tr>
<td>F₁</td>
<td>A=(π*φ^2)/4</td>
<td>1.66106E-05 m^2</td>
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<tr>
<td>F₀/F₁</td>
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<td>0.004</td>
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<tr>
<td>F₁/F₀</td>
<td></td>
<td>227.465735</td>
</tr>
<tr>
<td>l</td>
<td>1.5 mm</td>
<td>0.0015 m</td>
</tr>
<tr>
<td>I/Dh</td>
<td></td>
<td>4.9180</td>
</tr>
<tr>
<td>ρ</td>
<td></td>
<td>1050 Kg/m^3</td>
</tr>
<tr>
<td>qₘ</td>
<td>1 g/s</td>
<td>0.001 Kg/s</td>
</tr>
<tr>
<td>w₁</td>
<td></td>
<td>0.0573 m/s</td>
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<tr>
<td>I^-8</td>
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<td>3.90184E+22</td>
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<tr>
<td>φ(l')</td>
<td></td>
<td>0.785</td>
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<tr>
<td>τ</td>
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<td>0.393</td>
</tr>
<tr>
<td>u</td>
<td>0.000000014 m^2/s</td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td>1883.888</td>
<td></td>
</tr>
<tr>
<td>λ</td>
<td></td>
<td>0.034</td>
</tr>
<tr>
<td>ζ</td>
<td></td>
<td>105953.1229</td>
</tr>
<tr>
<td>Δp</td>
<td>Δp=(ζ<em>p</em>w₁^2)/2</td>
<td>182862 Pa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.83 bar</td>
</tr>
</tbody>
</table>
The expected parabolic behavior for a liquid pressure drop is observed here.

Work in progress for the other geometries.
MEASURED PRESSURE DROP VERSUS MASS FLOW-RATE AT SATURATION TEMPERATURE -25°C
PROS AND CONS

HYDRAULIC RESISTANCE ADDED AT THE INLET

CAPILLARY PIPE

- **Usually adopted solution**
- Require two connections at both sides
- Additional risk of leakage
- Can be long
- Can need to be coiled to reduce the necessary space

FLOW RESTRICTOR

- Less used in present tracker detectors
- A gasket (VCR) can become a restrictor
- Small diameter orifice => risk of clogging

- **IT IS MANDATORY**
  - To use proper filtering elements
  - To use a pure fluid (no moisture)
  - Take care of the cleanness of the plant lines
  - Vacuum the lines before filling
LHCb UT
• Manifold and connection pipe **prototype is under construction**
• Prototypes will be used at CERN for integration and cooling test

ATLAS ITk Pixel Encap
• Distribution system in this detector is **inside the active area**
• Titanium CO$_2$ piping
• We’re going to make **thermal-hydraulic characterization** of Half-Ring prototypes on the CO$_2$ Baby-demonstrator

Under study:
• the **use of flow restrictors** alternative to capillary pipes
• the feasibility to **embed an orifice into the electrical breaker**

General
• On BD cooling plant we’ll try to **extend the measurements on flow restrictors at larger flows**
• Define a spreadsheet for pressure drop predictions
Acknowledgements

Special thanks to the CERN cooling team always supporting our work
Thanks for the Attention

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Back-up slides =>
ESTIMATION OF THE FLOW REYNOLDS NUMBER

REYNOLDS NUMBER BEFORE THE ORIFICE

Mass flow-rate (g/s)
CO₂ PHYSICAL PROPERTIES:

Saturation Properties for Carbon Dioxide CO₂
In the range of interest: -20 °C …-40 °C

CO₂ physical properties used in the pressure drop calculation:
• Density
• Dynamic viscosity
(note: Kinematic viscosity is the ratio of dynamic viscosity to density)

Next slides show some plots captured from the web site of National Institute of Standards and Technology (NIST)

CO₂ temperature = -25 °C
CO₂ Density at -25°C = 1040 Kg/m³
CO₂ Viscosity at -25 °C = 150 micro Pa s
CO₂ DENSITY

Fluid Data

Data on Saturation Curve

1116 kg/m³ LIQUID PHASE
1040 kg/m³ VAPOUR PHASE
1032 kg/m³

Auxiliary Data

Reference States, IIR Convention

Enthalpy $H = 200 \text{kJ/kg at } 0^\circ \text{C for saturated liquid.}$
CO₂ Dynamic Viscosity:

Kinematic viscosity is the ratio of *dynamic viscosity to density*.
CO₂ Enthalpy liquid to vapour:

**This figure is used to calculate the needed cooling mass flow-rate**

- For a given dissipated power
- And for a given CO₂ exhaust (detector outlet) vapour fraction, i.e. \( X_{\text{out}} = 30\% \)

- Dissipated power \( Q \) (W)
- Outlet vapour fraction \( X_{\text{out}} \) (%)
- Latent heat of vaporization \( h_{\text{l-v}} = h_{\text{l-liquid}} - h_{\text{vap}} \) (J/g)

\[ \text{calculated FLOW (g/s)} = \frac{Q \text{ (W)}}{0.30 \times h_{\text{l-v}} \text{ (J/g)}} \]

- \( h_{\text{l-v}} = 313 \text{ J/g} \)
- \( h_{\text{l-v}} = 303 \text{ J/g} \)
- \( h_{\text{l-v}} = 283 \text{ J/g} \)

- \(-35°C\)
Inlet:
CO₂ liquid near to saturation

Outlet:
Vapour fraction
X_{OUT} = 30 % design point
50 % max

\[ \Gamma_{CO_2} = \frac{\text{POWER}}{X_{OUT}} \times \Delta H_{\text{LIQ-VAP}} \]

**CENTRAL “C” STAVE**
X_{OUT} = 30 % \Rightarrow
\Gamma = 75 \text{ W} / 0.3 \times 280 \text{ J/g} = \sim 0.9 \text{ g/s}

**LATERAL “A” STAVE**
X_{OUT} = 30 % \Rightarrow
\Gamma = 50 \text{ W} / 0.3 \times 280 \text{ J/g} = \sim 0.6 \text{ g/s}

\[ \Delta H_{\text{LIQ-VAP}} = \text{enthalpy difference liquid to vapour} \sim 280 \text{ kJ/kg} \]
At evaporation temperature of -25 °C
FLOW RESTRICTOR MEASUREMENT

OUTLET CONNECTION:
I.D. 2 mm PIPE COILED 1 LOOP

INLET CONNECTION:
SWAGELOK ORIFICE
0,01 INCH = 0,25 mm I.D.

<table>
<thead>
<tr>
<th>DATE</th>
<th>2016-04-19</th>
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<tbody>
<tr>
<td>STAVE</td>
<td>“C”</td>
</tr>
<tr>
<td>FLOW DIRECTION</td>
<td>UPWARD</td>
</tr>
<tr>
<td>INSULATION</td>
<td>ARMAFLEX</td>
</tr>
<tr>
<td>STAVE INLET</td>
<td>RESTRICTOR 0,254 mm</td>
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<tr>
<td>STEADY-STATE</td>
<td>OK</td>
</tr>
<tr>
<td>TRACI P SET POINT</td>
<td>17 barA</td>
</tr>
<tr>
<td>SATURATION TEMP</td>
<td>-23°C</td>
</tr>
<tr>
<td>HEATER POWER</td>
<td>75 W “nominal”</td>
</tr>
<tr>
<td>MASS FLOW-RATE</td>
<td>0,84 g/s (TRACI V.1 LIMIT)</td>
</tr>
<tr>
<td>CALCULATED X out</td>
<td>32 %</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>PRESSURE DROP</th>
<th>bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>INLET LINE WITH ORIFICE</td>
<td>2,875</td>
</tr>
<tr>
<td>EVAPORATOR (STAVE)</td>
<td>0,314</td>
</tr>
<tr>
<td>OUTLET LINE</td>
<td>0,034</td>
</tr>
</tbody>
</table>

THE MEASURED RATIO BETWEEN THE $\Delta P$ OF THE CIRCUIT COMPONENTS SHOULD GUARANTEE THE STABILITY IN THE EVAPORATING PARALLEL CHANNELS