LHCb UT Upgrade: studies and test for the detector cooling system design

Simone Coelli  (I.N.F.N. MILANO)
For the LHCb UT Group
• LHCb UT TRACKER UPGRADE
• THERMAL REQUIREMENTS
• THERMAL SIMULATIONS
• DETECTOR COOLING SYSTEM
• CO$_2$ COOLING TEST
UPSTREAM TRACKER
FOR THE LHCb UPGRADE

UT detector

is the replacement for the present Trigger Tracker (TT)

• Signals processed at the sensor level
• Low sensor temperature

Geometry

• 4 planar detection layers
• width 1.5 m * height 1.3 m

THIS PRESENTATION WILL FOCUS ON THE DETECTOR THERMAL MANAGEMENT
The detector cooling system has to:

- Extract the thermal power dissipated by read-out chips
- Keep the sensor temperature < -5 °C
  To prevent thermal runaway in presence of radiation damage
- Keep the temperature difference over the silicon sensors < 5 °C
- Keep the ASICs max temperature < 40 °C

Detector total power:

4192 ASICs ~ 0.8 W/each
+ cables + sensors + environment etc.
=> ~ 4 kW to be extracted + 25 % safety

Implementing:

- CO₂ evaporative cooling system
- CO₂ evaporation temperature - 25 °C
- local support design and material properties
- automatically satisfied with the adopted design and cooling temperature

CO₂ Cooling plant:

- 2-Phase Accumulator Controlled Loop
- Common development with LHCb VELO detector
STAVE DESIGN

ASICs read-out chips:
main contribution to the thermal dissipated power

Design concept exploits:
CO₂ evaporating inside a pipe passing underneath the ASICs

Highly conductive carbon foam (black)
Structural light-weight Core foam (gray)
Snake pipe embedded into the carbon foam

“SNAKE PIPE DESIGN”

Stave internal structure

COOLING PIPE: Titanium C.P. 2
I.D. 2 mm
O.D. 2,275 mm

please refer to the Ray Mountain talk at this Forum “Mechanics and Construction of the LHCb Upstream Tracker Detector”
Sensor mounted on both sides of the stave

4 ASICs read-out

Attended over the power/data bus cable (in brown)

8 ASICs read-out
CALCULATED THERMAL FIELD

Sensor temperatures in the central stave

A1.T3 Temperature gradient

for the more critical sensor A1.T3:

Referring to the cooling pipe temperature
Min $\Delta T \sim 1 ^\circ C$
Max $\Delta T \sim 6 ^\circ C$

$\Rightarrow$ TEMPERATURE ESCURSION OVER THE SILICON SENSOR = $\Delta T \sim 5 ^\circ C$

CURRENT LOCAL SUPPORT DESIGN SATISFIES THIS REQUIREMENT
OPTIMIZATION WORK IN PROGRESS
UT Detector can be split into two halves. We can identify 4+4 “half-plane” units - having 8 or 9 parallel staves.

**Top manifold**

**CO₂ exhaust**

**“half-plane” showing only the cooling system**

**Bottom manifold**

**CO₂ supply**

**CO₂ upward flow**
**STAVE ENERGY BALANCE**

**Inlet:**
CO\(_2\) liquid near to saturation

**Outlet:**
Vapour fraction
X\(_{OUT}\)
30 % design point
50 % max

**Mass flow-rate calculation:**
\[ \Gamma_{CO_2} = \text{Power} / X_{OUT} \times \Delta H_{\text{Liq-Vap}} \]

**Central “C” Stave**
X\(_{OUT}\) = 30 % =>
\[ \Gamma = 75 \text{ W} / 0,3 \times 280 \text{ J/g} = \sim 0.9 \text{ g/s} \]

**Lateral “A” Stave**
X\(_{OUT}\) = 30 % =>
\[ \Gamma = 50 \text{ W} / 0,3 \times 280 \text{ J/g} = \sim 0.6 \text{ g/s} \]

\( \Delta H_{\text{Liq-Vap}} \) = enthalpy difference liquid to vapour \( \sim 280 \text{ kJ/kg} \)
At evaporation temperature of - 25 °C
Differences between the evaporators

Pipe in the central stave:
- 6% longer
- 4 more 90° bends

Thermal load:
- Lateral stave 50 W
- Central stave 75 W (50% more)
For stability in evaporating parallel channels
**INLET connection lines MUST HAVE A PRESSURE DROP** bigger than the evaporation channels pressure drop (e.g. > 5 times)

To be obtained using **passive elements**.
Two options investigated:

1. **calibrated orifices**: concentrated pressure drops, inserted in the stave inlet line

2. **capillaries**: distributed pressure drops, Coiled between stave and manifold, or running outside the detector box to external manifold

**BOTH OPTIONS HAVE BEEN TESTED**
1. CO2 DISTRIBUTION USING CAPILLARIES

CAPILLARY selected
1/16” Swagelok pipes
AISI 316L
ID 0,88 mm
Thickness 0,35 mm

VCR FITTINGS
LASER WELDED ON CAPILLARIES
(RODOFILL-SAES GETTER Company)
2. DISTRIBUTION IMPLEMENTING CALIBRATED ORIFICES

compact design:
flow restrictor incorporated in the inlet connection line

SWAGELOK flow restrictors
For stability in evaporating parallel channels, OUTLET connection lines MUST HAVE MINIMUM PRESSURE DROP.

- AISI 316L PIPE
- ID 2.0 mm = the same as Titanium cooling pipe NO RESTRICTION
- OD 2.5 mm = minimum available thickness ($P_{\text{design}} = 100$ bar)

To increase the elasticity of the connections => COILING

VCR FITTINGS LASER WELDED ON PIPE (RODOFILL-SAES GETTER Company)
CO₂ COOLING TEST

CO₂ BOILING IN
• VERTICAL
• «SNAKE» PIPE
• 2 mm I.D.

THERMO-HYDRAULIC CHARACTERIZATION OF
• STAVE
• DETECTOR COMPONENTS PROPOSED FOR THE DESIGN

COOLING TEST SET-UP IN MILANO

TRACI V.1
2 P.A.C.L.
COOLING PLANT

POWER SUPPLY

COLD BOX

DAQ

TRACI LOCAL BOX-NEEDLE VALVES

INSTRUMENTED DUMMY STAVE UNDER TEST

10/11/2015 18:25
Fluid pressure transmitters
Piezo-resistive Keller 21Y
Output 4-20 mA; 0-80 bar

Fluid temperature transmitters
PT100-4wires Rodax
OD 4mm length 80 mm

CO$_2$ MEASUREMENT POINTS

STAVE OUTLET CO$_2$ EXHAUST LINES PRESSURE DROP

PF2
TF2

PF4
TF4

PF1
TF1

PF3
TF3

STAVE PRESSURE DROP

CO$_2$ FLOW TO THE STAVE - upward flow

STAVE INLET CO$_2$ SUPPLY CONNECTION PRESSURE DROP
20 “T” type Thermo-couples along the cooling pipe circuit

12 PT100-4wires

Glued on the external pipe wall using thermal paste $K = 5 \text{ W/mK}$
LHCb UT CENTRAL STAVE
PRESSURE DROP VS MASS FLOWRATE
ELECTRIC POWER 75 W

CENTRAL STAVE
FLOW-RATE FOR 30% Xout = 0.9 g/s
=> 0.33 bar STAVE PRESSURE DROP
CENTRAL STAVE PRESSURE DROP VS MASS FLOW-RATE AT SEVERAL POWER LOADS

WITHIN MEASUREMENT ERRORS THE DATA CONFIRM THE EXPECTED BEHAVIOUR
STAVE PRESSURE DROP VS POWER
FOR A FIXED MASS FLOW-RATE

"C" channel pressure drop vs power
mass flow-rate= 0.95 g/s
Pset= 16 bar

COOLING SYSTEM OPERATES INSIDE A STABLE OPERATIVE REGION
AND CAN ACCEPT 50 % EXTRA LOAD
Initial Mass flowrate = 0.9 g/s

1. OFF Power
2. ON Power = 75 W
3. OFF Power

when power is switched on the
Flow-rate decreases from ~0.9 to ~0.8 g/s

Stave pressure drop increase due to evaporation

Vice-versa the flow come back to initial value when the power is switched off
TO VERIFY THE ENERGY BALANCE CALCULATION:
GOING DOWN TO A SUFFICIENT LOW FLOW-RATE WE
REACH THE NON DESIDERABLE DRY-OUT REGION

OSCILLATING TEMP. ARE OBSERVED AT A CERTAIN POINT IN THE STAVE (PIPE WETTED
AND DRYED NEAR THE DRY-OUT REGION)

FROM THIS POINT CO₂ VAPOUR TEMPERATURE INCREASES IN TIME

EXPERIMENT IS THEN STOPPED BECAUSE THIS IS NOT A SUSTAINABLE OPERATIVE
SITUATION IN THE LONG TERM
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.

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<th>2016-04-19</th>
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<tbody>
<tr>
<td>STAVE</td>
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<tr>
<td>FLOW DIRECTION</td>
<td>UPWARD</td>
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<tr>
<td>INSULATION</td>
<td>ARMAFLEX</td>
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<tr>
<td>STAVE INLET</td>
<td>RESTRICTOR 0,254 mm</td>
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<tr>
<td>STEADY-STATE</td>
<td>OK</td>
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<tr>
<td>TRACI P SET POINT</td>
<td>17 bar A</td>
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<tr>
<td>SATURATION TEMP</td>
<td>-23°C</td>
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<tr>
<td>HEATER POWER</td>
<td>75 W “nominal”</td>
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<tr>
<td>MASS FLOW-RATE</td>
<td>0,84 g/s (TRACI V.1 LIMIT)</td>
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<tr>
<td>CALCULATED X out</td>
<td>32 %</td>
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<table>
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<th>PRESSURE DROP</th>
<th>bar</th>
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<tbody>
<tr>
<td>INLET LINE WITH ORIFICE</td>
<td>2,875</td>
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<tr>
<td>EVAPORATOR (STAVE)</td>
<td>0,314</td>
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<tr>
<td>OUTLET LINE</td>
<td>0,034</td>
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</table>

RATIO 1:10
RATIO 1:10

THE MEASURED RATIO BETWEEN THE Dp OF THE CIRCUIT COMPONENTS SHOULD GUARANTEE THE STABILITY IN THE EVAPORATING PARALLEL CHANNELS
CAPILLARY MEASUREMENT

DATE: 2015-10-09
STAVE: “C”
FLOW DIRECTION: UPWARD
INSULATION: ARMAFLEX
STAVE INLET: CAPILLARY 1/16”
STEADY-STATE: OK
TRACI P SET POINT: 16 bar
SATURATION TEMP: -28°C
HEATER POWER: 75 W “nominal”

CAPILLARY LENGTH = 6 m
PRESSURE DROP AT 0.45 g/s ~ 3 bar

CAPILLARY LENGTH = 1 m
PRESSURE DROP AT 0.84 g/s ~ 1.6 bar

Darcy–Weisbach equation works fine for the liquid phase into the capillary:

\[ h_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2g} \]

INLET CONNECTION:
CAPILLARY SWAGELOK PIPE
1/16 INCH = 0.88 mm ID

CAPILLARY PRESSURE DROP IS PROPORTIONAL TO THE CAPILLARY LENGTH
3 bar CAN BE OBTAINED USING A 2 m LONG 1/16 INCH
INCLINED STAVE OPERATION

TO VERIFY THE OPERATION OF THE COOLING SYSTEM IN THE REAL GEOMETRY CONFIGURATION FOR THE UT PLANES UTbV AND UTaU

+ 5° C.W.

- 5° C.W.

TEMPERATURES AND PRESSURES ~ CONSTANT IN TIME AFTER THE STAVE MOVEMENT
THE SYSTEM COMES BACK TO THE SAME STEADY-STATE OPERATION

THE STAVE COOLING SYSTEM IS NOT AFFECTED BY THE - 5° TO + 5° DISPLACEMENT FROM THE VERTICAL POSITION
Next test planned

Comparison of Stave A/B/C
- ID 2 mm pipe with 1 coil mounted both at the inlet and the outlet
- Calibrated orifice at the inlet
- Characterization of the stave circuit between the manifolds
- For the three different stave «flavours» A/B/C

Test with downward flow

Box insulation
- Make the cooling test without Armaflex insulation
- Controlled humidity cold box
- Fluxed with dry air
- More similar to the detector box
CONCLUSIONS

From the thermal management point of view:

- The design and test of all cooling related components of the UT detector is well advanced, in particular the manifold and distribution system.

- The correct operation of the CO_2 cooling system for a single stave with a snake pipe has been demonstrated by measurement and simulation.

We had these Engineering Design Reviews:

- «Stave construction EDR», CERN, 19 June 2015
- «LHCb CO2 cooling EDR», CERN, 3 December 2015

The «LHCb UT Detector Cooling requirements» document has been released.
IDEAS OR DREAMS

C.F.D.
COMPUTATIONAL FLUID-DYNAMIC STUDIES USING FLUENT
.. FOR TWO-PHASE EVAPORATING CO2

FILM THE BUBBLES
LOOK INTO THE EXHAUST LINE WITH A VIDEO-CAMERA
.. TO LOOK FOR VAPOUR FRACTION EXTIMATION

MICROPHONE FOR THE BUBBLES
USE THE PIEZO-RESISTIVE PRESSURE TRANSMITTERS AS “BUBBLES-METERS”
.. NEED A DIFFERENT ACQUISITION SYSTEM

R&D
STUDENTS FROM POLITECNICO DI MILANO FOR MORE GENERAL CO2 STUDIES
.. COULD BE IMPLEMENTED IN SIMULATION CODE LIKE COBRA
CONTRIBUTIONS

Colleagues from the INFN Milano Design & Mechanical Dpt.
Carlo Gesmundo (lines design..)
Andrea Capsoni (cooling system)
Mauro Monti (FEAs and design)
Ennio Viscione (system construction)

For the Power and DAQ system, Labview software:
Mauro Citterio
Alessandro Andreani
Fabrizio Sabatini
Andrea Merli

I’d like to acknowledge the CERN EP-DT cooling team and colleagues from other institutes in the LHCb Collaboration.
THANKS FOR THE ATTENTION.

BACK-UP SLIDES =>
UT detector CO2 Cooling Test Results

DATE: 2016-04-19
STAVE: "C"
FLOW DIRECTION: UPWARD
INSULATION: ARMAFLEX
STAVE INLET: RESTRICTOR 0.254 mm
STEADY-STATE: OK
TRACI P SET POINT: 17 bar
SATURATION TEMP: -23°C
HEATER POWER: 75 W "nominal"
MASS FLOW-RATE: 0.84 g/s (~ nominal)

<table>
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<tr>
<th>channel delta p</th>
<th>0.314</th>
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<tbody>
<tr>
<td>orifice delta p</td>
<td>2.875</td>
</tr>
<tr>
<td>outlet delta p</td>
<td>0.034</td>
</tr>
</tbody>
</table>
There are 2 cooling pipe geometries:

**A, B type**
- Number: 60 staves
- Pipe Length 2.82 m
- Heated length = 14 * ~85 mm = 1.19 m

**C type**
- Number: 8 central staves
- Pipe Length 3 m
- Heated length = 16 * ~85 mm = 1.36 m

- **Titanium C.P. 2 from HIGH-TECH U.K. Company**
  - I.D. 2,025 mm
  - O.D. 2,275 mm
- Cooling snake pipe produced starting from a 3.1 m long straight pipe annealed ¼ hard.
- Bending radius R = 10 mm

- Bended pipes fit very well in the geometry mask after the bending

Optimal pipe material as for:
- high radiation length
- low thermal expansion coefficient
- Big strength
- Good thermal conductivity
- Thin pipe availability

Titanium has a C.T.E. = 9.4 ppm/K
Stainless Steel C.T.E. = 17 ppm/K

This determines its best performance from the contraction point of view
Ti Cooling pipe free contraction is ~ 0.8 mm
BENDING TITANIUM PIPES
Fit very well in the geometry mask
Titanium to swagelok 1/8 glued + stiffener

Dummy stave with attached reworked fittings on the Titanium snake pipe (dummy C central stave)

Glued joint ARALDITE 2011 Ti pipe –SS reworked dummy fitting tested without stiffener up to 200 bar for several times
STAVE OUTLET CO2 CONNECTION PIPE

OUTLET PIPING, design choice:

2 mm ID
=no diameter restriction

2,5 mm OD
0,25 mm thickness= minimum commercial available
Weldable, Pdesign 100 bar ok factor ~ 5

S.S. AISI 304L annealed (and post-bending annealing foreseen in final system)

If ok
pipe procurement
We buy
30 m = 15 pipes 2 m long
min quantity
From “Castiglioni” company

If ok
welding prototyping
We’re asking offer to “Real – Vacuum” company
To produce prototyp
MICRO TIG welded
Swagelok 1/8 inch VCR fitting – pipe stave interface
Welded to the manifold (no disconnection on manifold side)
PIPE TEMPERATURE SENSORS INSTALLED

T_x = TEMPERATURE
position x = 1 to 20

MODEL:
Thermocouple “T” type
2 wires

<table>
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<tr>
<th>Type</th>
<th>Material 1</th>
<th>Material 2</th>
<th>Color Code</th>
<th>Minimum</th>
<th>Maximum</th>
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<tr>
<td>J</td>
<td>Iron</td>
<td>Constantan</td>
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<td>6</td>
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<td>K</td>
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<tr>
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<tr>
<td>E</td>
<td>Chrome</td>
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<td>-260</td>
<td>900</td>
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</table>
TRACI V1
Mass flowrate measurement
By Coriolis flowmeter
Pressures steady-state Nominal power and flux
one of the measurement points

<table>
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<tr>
<th>mbar</th>
<th>mbar</th>
<th>mbar</th>
<th>mbar</th>
<th>mbar</th>
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<tbody>
<tr>
<td>PF1</td>
<td>PF2</td>
<td>PF3</td>
<td>PF4</td>
<td>PF1</td>
<td>PF2correction-0,123</td>
<td>PF3correction-0,044</td>
</tr>
</tbody>
</table>

.... Only some data are posted here ....


old
needle
Valve in the
inlet line

mbar PF1

---

DELTA PF1-PF2corr
Stave SNAKE PIPE GEOMETRY

«C» central stave
8 on a total of 68 staves
under test

Titanium C.P. 2
I.D. 2.025 mm
O.D. 2.275 mm

Pipe Length 3 m
Heated length = 16 * ~85 mm = 1.36 m

Pipe Length 3 m
Heated length = 16 * ~85 mm = 1.36 m
Stave SNAKE PIPE GEOMETRY

Identical for the «A» «B» staves
All the other detector stave apart the 8 central staves

Pipe Length 2.82 m
Heated length = 14 * ~85 mm = 1.19 m
COBRA simulation for 100% power and nominal 0.9 g/s flux

horyzontal straight pipe correlation

Using full length 3 m (more correct for friction calculation)

Consistent with Calculated Xout = 28%
COBRA simulation for 100% power and nominal 0.9 g/s flux
horizontal straight pipe correlation

Using heated length 1.36 m, more correct for heat exchange
Heating a flow from liquid to gas

**Pressure (Bar)**

- Liquid
- Gas
- 2-phase

**Enthalpy (J/kg)**

**Temperature (°C)**

- Liquid Superheating
- Low ΔT
- Fluid temperature
- Target flow condition
- Dry-out zone
- Sub cooled liquid
- 2-phase liquid / vapor
- Super heated vapor

Increasing ΔT (Dry-out)
PURE CO2 SATURATION CURVE
TEMPERATURE AND PRESSURE INSIDE THE EVAPORATION CHANNEL

=> 15 TO 20 bar COOLING FLUID OPER. PRESSURE

- 20 °C TO - 30 °C COOLING FLUID OPER. TEMP.
THE LATENT HEAT OF VAPORIZATION FOR CO2 CAN BE KNOWN FROM THE CO2 PRESSURE-HENTALPY DIAGRAM

IN THE RANGE OF INTEREST
DELTA H liq. => vap. = 280-300 kJ/kg
CO2 physical properties

Set point on TRACIv1:
Accumulator pressure P = 15 bar ABS / T saturation= -28.5 °C

Henthalpy liquid (X=0)
Henthalpy vapour (X=100%)

### CO2 physical properties

**Input Data**

- **Select function:**
  - 1. function (p, x)

<table>
<thead>
<tr>
<th>Property name</th>
<th>Property ID</th>
<th>Results (Liquid)</th>
<th>Results (Vapor)</th>
<th>Units (SI)</th>
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<tbody>
<tr>
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<td>p</td>
<td>15.0000000000</td>
<td>15.0000000000</td>
<td>bar</td>
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<tr>
<td>Temperature</td>
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<td>-28.5199041122</td>
<td>°C</td>
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<td>1069.3872426404</td>
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<td>0.0009251150</td>
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<td>Specific enthalpy</td>
<td>h</td>
<td>-370.2278554471</td>
<td>-370.2278554471</td>
<td>kJ/kg</td>
</tr>
</tbody>
</table>

**Calculated exhaust vapour fraction Xout**

\[
X_{out} = \frac{(h_{out} - h_{in})}{\delta h_{L-V}}
\]

\[
(h_{out} - h_{in}) = \frac{Power}{F}
\]

\[
F = \text{mass flowrate} \quad \text{g/s}
\]

\[
\text{Power} = \text{electrical heaters power} \quad \text{W}
\]

=> \[
X_{out} = \frac{(Power/F)}{\delta h_{L-V}}
\]

### Delta h L-V @15 bar ABS

<table>
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<th>Property</th>
<th>Value</th>
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<tr>
<td>Delta h L-V @15 bar ABS</td>
<td>300 J/g</td>
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</tbody>
</table>

**Xout**

\[
X_{out} = 75 / (300 \times F) \quad \frac{W}{(J/g \times g/s)} = 1
\]
UT detector CO2 Cooling Test Results

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<th>TEMPERATURE DROP</th>
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<tbody>
<tr>
<td></td>
<td>bar</td>
<td>°C</td>
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<tr>
<td>INLET LINE WITH ORIFICE</td>
<td>2,875</td>
<td>4,9</td>
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<tr>
<td>EVAPORATOR CHANNEL</td>
<td>0,314</td>
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CO₂

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PF5

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<td>TF1</td>
<td>TF2</td>
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<td>TF4</td>
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UT detector CO2 Cooling Test Results

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

PIPE TEMPERATURES

T11 = OVER ALUMINUM PLATE WITH 6 HEATERS
DUMMY STAVE HEATING SYSTEM

«C» DUMMY STAVE WITH HEATERS
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<td>CFRP</td>
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<td>65</td>
<td>410</td>
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<td>-0.765</td>
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<td>32</td>
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<td>LAMINATE</td>
<td>Lay-up (0/90/0)</td>
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<td>175</td>
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<td>E [GPa]</td>
<td>Poisson Ratio PR</td>
<td>ρ [Kg/m³]</td>
<td>CTE [ppm/K]</td>
<td>K [W/m K]</td>
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</table>
Central stave energy balance
INLET = OUTLET MASS FLOWRATE in different cooling flow configurations

Q = 85 W
X = 30 %
H lv = 280 kJ/kg

Coolant Mass flow rate always

⇒ \( \Gamma = 1 \, \text{g/s} \)

Given the same boundary conditions
Design option:
2 - Manifolds both on the bottom (ADDING LOCAL PRESSURE DROPS) and on the top

Design option:
3 - Capillaries both on the bottom and on the top
Glued connection between Titanium pipe and a «dummy swagelok VCR fitting»
Preliminary qualification

Then 2 VCR will be glued on the bended pipe sin the dummy staves
INFRARED THERMO-CAMERA PICTURE
COLD-BOX OPEN
THERMAL FEA
THERMAL LOADS AND BOUNDARY CONDITIONS

Read-out chip POWER:
+ 0.768 W / ASIC

POWER dissipated in the FLEXBUS:
+ 10 % of transported power
(i.e. 8 * 0.768 = 6.14 W)

SENSOR SELF HEATING:
T1 = + 0.261 W
T2 = + 0.171 W
T3 = + 0.135 W

COOLING PIPE TEMPERATURE external wall SET TO 0 °C
=> CALCULATED TEMPERATURES ARE A DELTA REFERRED TO THIS TEMPERATURE
Hypothesis: 128 WIREBONDS PER ASIC - Diam. 25 μm

Total cross section area per ASIC: \( A = 0.062832 \text{ mm}^2 \)

Total cross section area per ASIC of the FE model: \( A_m = 1.130976 \text{ mm}^2 \)

Factor: \( A_m / A = 18 \)

K Aluminum = 210 W/m K

Equivalent ribbon: \( K_{eq} = 210 / 18 = 11.7 \text{ W/m K} \)
ASICs TEMPERATURE

ASIC temperature calculated $\Delta T = 21.2 \, ^\circ C$ over the cooling pipe temperature

**Thermal Figure of Merit**

$$\text{TFoM} = \frac{\Delta T}{P} \, [^\circ \text{C}\cdot \text{cm}^2/\text{W}]$$

$\Delta T =$ max temperature difference between cooling tube and power dissipation source $[^\circ \text{C}]$

$P =$ thermal power flux $[\text{W/cm}^2]$

meaningful only when $P$ is not zero

**Valid only under the ASICs:**

$P$ under the ASICs $= 1.25 \, \text{W/cm}^2$

$\Delta T = 21.2 \, ^\circ C$

$\Rightarrow \text{TFoM} \approx 17 \, [^\circ \text{C}\cdot \text{cm}^2/\text{W}]$
RESULTS SUMMARY TABLE (for «C» central stave, sensors T1, T2, T3)

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<td>CERAMIC STIFFENER WITH SLITS</td>
<td>PBN - THICKNESS 500 μm</td>
<td>2.2</td>
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<td>AlN- THICKNESS 250 μm</td>
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<td>CERAMIC STIFFENER SEPARATED INTO TWO PARTS</td>
<td>PBN - THICKNESS 500 μm</td>
<td>2.0</td>
<td>1.9</td>
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<td>AlN- THICKNESS 250 μm</td>
<td>1.8</td>
<td>1.8</td>
<td>2.2</td>
<td>19</td>
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</table>

CONCLUSIONS:

- THE TEMPERATURE DIFFERENCE ACROSS THE SENSORS IS ALWAYS ACCEPTABLE FOR THE INNERMOST SENSORS T1 AND T2 (around 2 °C)
- THE TEMPERATURE DIFFERENCE ACROSS THE SENSOR T3 (in the central stave) ACCEPTABLE FOR BOTH THE CERAMIC MATERIALS IN THE DESIGN GEOMETRY WITH SLITS (around 5 °C)

=> Both PBN and AlN solutions provide efficient heat transfer

- WITHOUT SLITS THE TEMPERATURE DIFFERENCE WORSEN. SENSOR T3 becomes critical in «C» stave
- AlN IS BETTER THAN PBN from the thermal point of view.
- ASICs TEMPERATURE ARE ALWAYS WITHIN SPECIFICATION. Operative temp. cooling pipe will be ~ -15 °C, ASICs ~ +5 °C, with a large margin against the limit of 40 °C.
FEA DETAIL

Identification of the criticality => optimization of the design - extension of the carbon foam under the sensor

Local sensor thermal field

heat flux from ASICS through the stiffener
DETECTOR TEMPERATURE FIELD
F.E.A. SIMULATION
COOLING PIPE TEMPERATURE SET TO 0 °C
=> TO SEE THE DETECTOR DISTRIBUTION OF TEMPERATURE

- VERSION V.5
- L-SHAPED SENSOR SUPPORT
- CERAMIC MATERIAL PBN /PYROLITIC BORON NITRIDE

⇒ DETECTOR FACEPLATE AND STRUCTURE IS ALWAYS 1-6 °C OVER THE COOLING PIPE TEMPERATURE
⇒ SENSOR TEMPERATURE IS 1-7 °C OVER THE COOLING PIPE TEMPERATURE

TO RESPECT REQUIREMENT WITH MARGINS AND TAKING IN ACCOUNT CO2 INTERNAL PIPE H.T.C. => COOLING PIPE < 20 °C

REQUIREMENT MAX
SENSOR TEMP < -5 °C

MIN SENSOR TEMP ~< -10/-15 °C

⇒ DELTA T ACROSS SENSOR AROUND 5-10 °C
THERMO-STRUCTURAL FEA
MAX DISPLACEMENT IN THE SENSOR A1.T3: 150 μm
almost all in the vertical direction Z axis, out of sensor plane
Thermo mechanical sensor thermal deformation

EQUIVALENT VON-MISES STRESS CALCULATED IN THE SILICON SENSOR A1.T3:
1 e-5 MPa IS THE MAXIMUM VALUE, NEAR THE WIRE-BONDING MEDIUM STRESS LEVEL AS LOW AS FRACTION OF A PASCAL

=> Conclusion:
Calculated deformations of the sensor, in vertical direction, are not representing a particular concern.
PIECE OF THERMO-MECHANICAL DEFORMATION

- PIPE TEMPERATURE SET TO - 25 °C
- THERMAL FIELD CALCULATED AT NOMINAL POWER
- THEN USED FOR THE STRUCTURAL FEA

MAXIMUM DEFORMATION = 0.63 mm
TITANIUM PIPE
DELTA T = - 60°C
MAX TOTAL DEFORMATION: 0.81 mm

TITANIUM PIPE
MDP = 10 MPa
MAX TOTAL DEFORMATION: 0.51 mm
Thermo mechanical F.E.A. - full length stave structural studies

H.M. CFRP K13C-RS3
DELTA T = - 60°C
MAX TOTAL DEFORMATION: 0.20 mm

=> effect induced by the pipe contraction

H.M. CFRP K13C-RS3
MDP = 10 MPa
MAX TOTAL DEFORMATION: 0.01 mm

=> Deformation induced by the pipe pressurization is almost negligible
FULL STAVE
THERMO-MECHANICAL
DEFORMATION
FULL STAVE UT STAVE type C THERMAL ANALYSIS RESULTS
SENSORS TEMPERATURE

PIPE TEMPERATURE SET TO -25 ºC
ONE END OF THE STAVE HAS BEEN CONSTRAINED AS FIXED SUPPORT. THE OTHER END HAS BEEN CONSTRAINED AS FIXED IN TRANSVERSAL (X) AND NORMAL TO MODULE (Z) DIRECTIONS AND FREE TO SLIDE IN THE LONGITUDINAL (Y) DIRECTION. FOR BOTH ENDS EITHER THE TWO PLANAR FACES OF THE STAVE MOUNT IN ALUMINUM ALLOY HAVE BEEN CONSTRAINED.
UT STAVE type C - THERMO-MECHANICAL ANALYSIS
UY RESULTS

MAXIMUM Y DEFORMATION
UY = 0.27 mm

SLIDING ALLOWED ALONG Y

DEFORMATION AMPLIFICATION SCALE: 65
THE THERMAL MODEL HAS BEEN SWITCHED IN THE MECHANICAL MODEL, CHANGING THE ELEMENTS TYPE BUT NOT THE NODES QUANTITY AND LOCATIONS.

THE LOAD IS THE THERMAL FIELD OBTAINED BY THE THERMAL ANALYSIS AND IMPORTED IN THE MECHANICAL MODEL, NODE BY NODE.

THE COEFFICIENTS OF THERMAL EXPANSION OF THE MATERIALS HAVE BEEN ATTRIBUTED.
STAVE MODAL ANALYSIS
PHASE CHANGE
THERMAL INTERFACE
THERMFLOW T725
UNDERNEATH THE
STIFFENERS

GLUE DOT NE0001
UNDERNEATH THE
FREE
SENSORS CORNER
STAVE MODAL ANALYSIS

STAVE MODAL FREQUENCY SPECTRUM

MODE 1
16.5 Hz
MODE 1
16.5 Hz

MODE 2
44.2 Hz

MODE 3
55.5 Hz

MODE 4
83.8 Hz

MODE 5
100.5 Hz

MODE 6
131.7 Hz