New CERN CO$_2$ Test Facility for Mini- and Micro-channels

Forum on Tracking Detector Mechanics
25 - 27 June 2018
Valencia

Desiree Hellenschmidt, Paolo Petagna

EP-DT-FS
CERN, Geneva, Switzerland
REQUIRED: Internal standard to test mini- and micro-channel cooling devices
MOTIVATION
MOTIVATION

MAIN OBJECTIVES:

Characterization of thermal properties and pressure drop behavior of mini- and micro-channel cooling devices

Reliable experimental data for model updates and more optimal design parameters of future mini- and micro-channel evaporators
Definition of **common needs** for the institutes

Resources available at CERN

Definition of the *state-of-the-art* test stand

*active re-definition of a high quality test stand*
Common parameters of interest

- mass flux
- fluid pressure
- fluid temperature
- heat dissipation
- pressure drop

Resources available at CERN

- evaporative CO$_2$ as chosen refrigerant
- Transportable Refrigeration Apparatus for CO$_2$ Investigation = TRACI developed at CERN
  - mass flux is adjustable (by-passing)
  - temperature range from ~ +20 to -25 °C
  - CO$_2$ is re-circulated
Controlled measurements are ensured by following components:

- **2-phase CO₂**
  - Transportable Refrigeration Apparatus for CO₂ Investigation

- **Vacuum vessel**
  - Adiabatic test conditions for more accurate heat transfer measurements

- **P & T sensors**
  - High precision measurements for pressure & heat transfer

- **Flow meter**
  - Direct high precision measurement of the mass flow rate

- **IR Camera**
  - Heat transfer visualization

- **High speed cam**
  - Visualization of details on bubble dynamics (100 000 fps)

+ **Data acquisition**
TEST FACILITY

- Differential pressure sensor
- Absolute pressure sensors
- Temperature sensors on the experiment

Mock-up heater (Joule Heater)
- Temperature sensors in the flow (1-6)
- Experimental by-pass
- Experimental by-pass
- Two Peltier elements as pre- and post-heater
Fig. 2 Schematic of the new CO₂ test facility inside vacuum vessel

Fig. 3 Experiment section inside vacuum vessel (Mar 2017)
TEST FACILITY

two cameras & two vessel windows for visualization:

HIGH SPEED CAMERA

INFRA-RED CAMERA

AMTIR-1 window

Borosilicate window

EXPERIMENT
TEST FACILITY

DATA ACQUISITION with LabVIEW®

- experiment sensors
- flow meter
- vacuum level
- control of Peltier & Joule heater
- online evaluation of fluid state
- adjustable data acquisition frequency

→ MATLAB® code for analysis
Fig. 4 New test facility for evaporative CO$_2$ flow measurements in mini- and micro-channels (I) (Mar 2017)

Fig. 5 New test facility for evaporative CO$_2$ flow measurements in mini- and micro-channels (II) (Mar 2017)
Fig. 6 New test facility for evaporative CO$_2$ flow measurements in mini- and micro-channels (III) (Jun 2018)
BEFORE

Mar 2017

AFTER

Jul 2018
**TEST FACILITY Updates & Upgrades**

- Air-conditioned laboratory
- Thermally insulated fluidic feed through
- Peek inserts
- Dielectric fittings
- Analysis and exchange of RTDs
- New stainless steel flange
- Optional Multi-Layer-Insulation (MLI)
- adhesive coated foil *Metal Velvet™*
- Spacer flange
- New heater for TRACI

**Most important upgrades for more accuracy**
Analysis and exchange of RTDs

- Standard approach in CO$_2$ cooling plants at CERN:
  Pt100 in 4-wire configuration with stainless steel shaft

- New CO$_2$ test facility:
  Same sensors with custom-made measurement tip

→ However:
Pt100s showed higher temperature in vacuum compared to tests at atmospheric conditions
Analysis and exchange of RTDs

![Graph showing temperature vs. time for different RTDs](image)

Fig. 7 Standard RTD with stainless steel shaft
Analysis and exchange of RTDs

Fig. 7 Standard RTD with stainless steel shaft
Fig. 7 Standard RTD with stainless steel shaft
TEST FACILITY Updates & Upgrades

----- = DAQ off

Fig. 7 Standard RTD with stainless steel shaft
Error No. 1: Insertion error of shafted sensors

Error No. 2: Self-heating effect of RTDs
Error No. 1: Insertion error of shafted sensors

- **Solution: New custom-made RTDs**
  - bare Pt100 sensing element directly in flow
  - PEEK sensor housing
  - Filled with glue and CO₂ ‘resistant’ epoxy
  - Electrically & thermally insulated from remaining circuit

Error No. 2: Self-heating effect of RTDs

- **Solution: New multiplexing board**
  - flexible powering scheme for sensors possible
  - thus no long-term overheating of sensors
  - more accurate temperature measurements
Solution: New custom-made RTDs
RESEARCH PLAN

GOALS for experimental research on evaporative flow of CO$_2$ in mini- and micro-channels at CERN:

- Create a **larger and reliable database** for CO$_2$ pressure drops, heat transfer coefficient and flow patterns in mini- and micro-channels for model upgrades.

- **Extend research** towards negative fluid temperatures and micrometer sized channel diameters.

- Find and test a theoretical **micro-channel definition**.
STEP 1 : Test simple single channels / tubes (ID < 2 mm)
To address the complexity of the physical processes occurring in micro-channels and for their better understanding.

STEP 2 : Test more complex channel geometries
To address the immediate need for micro-channel cooling in HEP experiments using the gathered insights and results from Step 1.
STEP 1 : Test simple single channels / tubes (ID < 2 mm)

To address the complexity of the physical processes occurring in micro-channels and for their better understanding

STEP 2 : Test more complex channel geometries

To address the immediate need for micro-channel cooling in HEP experiments using the gathered insights and results from Step 1
## RESEARCH PLAN

### STEP 1:

#### CIRCULAR SINGLE CHANNELS (200 mm)

<table>
<thead>
<tr>
<th>Stainless Steel</th>
<th>Glass (Borosilicate)</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID [mm]</td>
<td>OD [mm]</td>
<td>ID [mm]</td>
</tr>
<tr>
<td>0.13</td>
<td>1.58</td>
<td>0.1</td>
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<tr>
<td>0.25</td>
<td>1.58</td>
<td>0.15</td>
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<tr>
<td>0.5</td>
<td>1.58</td>
<td>0.2</td>
</tr>
<tr>
<td>0.75</td>
<td>1.58</td>
<td>0.3</td>
</tr>
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<td>1.58</td>
<td>0.5</td>
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<tr>
<td>1.5</td>
<td>3.175</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>3.175</td>
<td>0.8</td>
</tr>
</tbody>
</table>

#### SQUARED SINGLE CHANNELS (200 mm)

<table>
<thead>
<tr>
<th>Glass (Borosilicate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inner cross-section [mm]</td>
</tr>
<tr>
<td>0.1 x 0.1</td>
</tr>
<tr>
<td>0.8 x 0.8</td>
</tr>
<tr>
<td>0.3 x 0.3</td>
</tr>
<tr>
<td>0.2 x 0.2</td>
</tr>
<tr>
<td>1.0 x 1.0</td>
</tr>
<tr>
<td>0.5 x 0.5</td>
</tr>
<tr>
<td>0.7 x 0.7</td>
</tr>
</tbody>
</table>
## RESEARCH PLAN

### RESEARCH PROPOSALS for STEP 1:

#### CIRCULAR SINGLE CHANNELS

<table>
<thead>
<tr>
<th>Material</th>
<th>ID [mm]</th>
<th>OD [mm]</th>
<th>ID [mm]</th>
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<th>ID [mm]</th>
<th>OD [mm]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.17</td>
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<tr>
<td></td>
<td>0.25</td>
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<td>0.15</td>
<td>0.25</td>
<td>0.5</td>
<td>1.58</td>
</tr>
<tr>
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<td>0.5</td>
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<td>0.33</td>
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<td>1.58</td>
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<td>3.175</td>
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<td></td>
<td>2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

#### SQUARED SINGLE CHANNELS

<table>
<thead>
<tr>
<th>Material</th>
<th>inner cross-section [mm]</th>
<th>wall thickness [mm]</th>
</tr>
</thead>
<tbody>
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<td>Glass (Borosilicate)</td>
<td>0.1 x 0.1</td>
<td>0.05</td>
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<tr>
<td></td>
<td>0.8 x 0.8</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>0.3 x 0.3</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.2 x 0.2</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>1.0 x 1.0</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.5 x 0.5</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.7 x 0.7</td>
<td>0.14</td>
</tr>
</tbody>
</table>

At various flow rates, heat loads & saturation temperatures

- Investigations on same tube material e.g. stainless steel but different diameters
- Investigations on same inner diameter e.g. 0.5 mm but different materials
- Investigations on approximately same cross-section but comparison between circular and squared cross-section
RESEARCH PLAN

At various flow rates, heat loads & saturation temperatures...

- Mapping of:
  - heat transfer coefficient vs. vapour quality
  - Pressure drop vs. vapour quality
  - also: possible instabilities
  - Visual mapping of heat transfer and bubble dynamics (High speed and IR camera)
  - ...

- Microchannel definition:
  - based on the preliminary work of Y. Moussy
  - a possible definition was found
  - by means of the bubble departure diameter
  - ...

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Carbon dioxide flow boiling in a single microchannel – Part I: Pressure drops
Maxime Ducoulombier, Stéphane Collasson, Jocelyn Bonjour, Philippe Haberschill

Carbon dioxide flow boiling in a single microchannel – Part II: Heat transfer
Maxime Ducoulombier, Stéphane Collasson, Jocelyn Bonjour, Philippe Haberschill

Experimental conditions and corresponding uncertainties:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Uncertainty</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_t$ (μm)</td>
<td>529</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>$L_C$ (mm)</td>
<td>191</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$T_{sat}$ (°C)</td>
<td>-10; -5; 0; 5</td>
<td>0.091; 0.089; 0.088; 0.088</td>
<td></td>
</tr>
<tr>
<td>$G$ (kg/m²s)</td>
<td>200–1400</td>
<td>2.3–1.9%</td>
<td>1.95%</td>
</tr>
<tr>
<td>$\Delta P$ (mbar)</td>
<td>0–150</td>
<td>0.27–0.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0–1500</td>
<td>2.9–4.5</td>
<td></td>
</tr>
<tr>
<td>$x$</td>
<td>0–1</td>
<td>1.5 (2.3³) to 0.5 %</td>
<td>0.85%</td>
</tr>
</tbody>
</table>

+ checking our data on their newly-developed correlation
RESEARCH PLAN

STEP 1 : Test simple single channels / tubes (ID < 2 mm)
To address the complexity of the physical processes occurring in micro-channels and for their better understanding.

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RESEARCH PLAN

STEP 2:

COMPLEX CHANNEL GEOMETRIES

Multi micro-channels produced and processed in cooperation with LPNHE Paris

Fig. 9 Wafer with micro-channels produced at FBK

Fig. 10 Connectorized micro-channels

Fig. 11 Micro-channel layout: Donut
RESEARCH PLAN

RESEARCH PROPOSALS for STEP 2:

- Visual mapping of bubble dynamics:

  ![Connector layout for multi-micro channels within CO₂ setup](image)

  Fig. 12 Connector layout for multi-micro channels within CO₂ setup

At various flow rates, heat loads & saturation temperatures

- Visual mapping of bubble dynamics:
RESULTS

STEP 1:

CIRCULAR SINGLE CHANNEL (L = 200 mm) in stainless steel: ID = 1 mm

Preliminary test matrix

Step 1.1: adiabatic single phase characterization
7 flow rates x 11 sat. temperatures, sub-cooling level: 2K

Step 1.2: two-phase research
9 flow rates x 11 sat. temperatures x 5 heat loads, sub-cooling level: ~ 0K

Fig. 13 stainless steel tube with 1 mm cross-section
RESULTS

**STEP 1:**

CIRCULAR SINGLE CHANNEL \((L = 200 \text{ mm})\) in stainless steel:

ID = 1 mm

**Step 1.1:** adiabatic single phase characterization: 1 example: \(T_{\text{sat}}\ 10\ ^\circ\text{C}\)

Comparison with macro-scale correlations for single phase pressure drop
RESULTS

STEP 1:

CIRCULAR SINGLE CHANNEL (L = 200 mm) in stainless steel:
ID = 1 mm
Step 1.2: two-phase research: 1 example: $T_{\text{sat}}$ 10 °C

![Graphs showing heat transfer coefficient vs. quality at different q values]
RESULTS

STEP 1:

CIRCULAR SINGLE CHANNEL ($L = 200 \text{ mm}$) in stainless steel:
ID = 1 mm
Step 1.2 : two-phase research: 1 example: $T_{\text{sat}}$ 10 °C

!!! Very high heat transfer coefficient !!!
RESULTS

STEP 1:

CIRCULAR SINGLE CHANNEL (L = 200 mm) in stainless steel:
ID = 1 mm

Step 1.2: two-phase research: 1 example: $T_{\text{sat}}$ 10 °C
Comparison with macro-scale correlation (developed for ID > 6 mm) for two phase heat transfer

$\rightarrow$ even in small channels CO$_2$ still ‘behaves’ as if flowing in bigger channels
due to its physical properties - here at 10 °C
RESULTS

STEP 1:

CIRCULAR SINGLE CHANNEL (L = 200 mm) in stainless steel: ID = 1 mm

Step 1.2: two-phase research: 1 example: $T_{\text{sat}} = 10^\circ \text{C}$
Comparison with micro-scale correlation (developed for ID = 0.5 mm) for two phase heat transfer

→ on the other hand: the data also fits micro-scale correlation
→ an indication that the obtained data lies between the macro- and micro-world
RESULTS

STEP 1:

CIRCULAR SINGLE CHANNEL (L = 200 mm) in stainless steel: ID = 1 mm

Step 1.2: two-phase research: 1 example: $T_{\text{sat}}$ 10 °C
Comparison with macro-scale correlation for two phase pressure drop

![Graph showing two phase pressure drop with measured data and Friedel correlation. Mean deviation in %: 7.](image-url)
CONCLUSION

✓ Test stand allows for a wide range in saturation temperature/pressures

✓ Setup to test mini- and micro-channel cooling devices was and is ever upgrading, but is now in a very good state to do some interesting research on it

✓ Mini- and micro-channels of different materials & geometries can be tested

✓ Some quite ambitious research plan lies ahead

✓ Research program launched for first tests

✓ Don’t rely on old - *but so far sufficient* - methods (RTDs)
• Create a **larger and reliable database** for model upgrades

• Use findings for **better understanding** of the physical behaviour of the flow in $\mu$-channels

• **Optimize design parameters** of future micro-channel evaporators

→ Towards **more efficient** detector cooling