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New insights on boiling carbon dioxide flow in mini- and micro-channels for optimal silicon detector cooling

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Introduction

- Along with the general mass and volume minimization, the thermal management needs of future silicon detectors are steadily increasing.
- This requires highly effective active cooling in very small channels.
- CO₂ in boiling state has been adopted as preferred refrigerant for the future generations of silicon detectors at the LHC.
- However, available data on CO₂ boiling in small channels is too limited – made difficult by the high pressure of CO₂ and often affected by too large measurement uncertainties – to allow for developing reliable predictive models.
- To confront these shortcomings a long-term experimental study has been launched with the ambitious objective of developing a deeper understanding of the properties of boiling flows of CO₂ in small channels.

Experimental Approach

The properties of evaporative CO₂ are studied within:
1. Simple small-diameter tubular evaporators (stainless steel, L = 0.2 m)
2. Complex multi-micro-channel cooling devices (silicon-substrate bonded to glass for visualization purposes).

- Both applications are highly relevant for HEP experiments.
- Results from the more basic single-channels can complement the rather multifaceted findings from the multi-micro-channels and vice versa.
- Thus it is possible to address the need of a deeper understanding of CO₂ boiling properties at mini- and micro-scales at all temperatures of interest on various levels.

Experimental Setup

A versatile new test setup was built with the following main components:

- Tubular evaporators
- Tubular instrumentation
- Vacuum vessel for adjustable test conditions for flow & heat transfer measurements
- High precision measurements for flow & heat transfer applications
- Visualization of details on bubble dynamics up to 100 000 frames per second (fps)
- Interchangeable apparatus for CO₂ investigation (TRACI)

The schematic layout of the test stand is shown below with the interchangeable experimental section at its core.

Studied Parameters

The test range for the two different detector cooling approaches is for tubular evaporators:
- Saturation temperatures (T_sat) from +15 to -25°C, mass fluxes from 1200 to 100 kg/m²s and heat fluxes from 5 to 35 kW/m².

Multi-micro-channels:
- Saturation temperatures from +15 to -25°C, mass flow rates of 0.1 g/s and 0.3 g/s and surface power densities from 1 to 5 W/cm².

Following parameters are studied with an unprecedented level of accuracy (experimental uncertainty below 10% -- typically ~ 20%):
- Heat Transfer Coefficient (h)
- Pressure drop (Δh)
- Bubble dynamics in the channels

Combination of results leads to new insights on CO₂ boiling in small channels and its dependency on T_sat.

Parametrical Results

EXAMPLE: Tubular evaporators

- 1 mm inner diameter (ID) stainless steel tube, L = 0.2 m
- Heat Transfer Coefficient (h)
- Pressure drop (Δh)
- Bubble dynamics with standard correlation

EXAMPLE: Multi-micro-channels

- 200 µm x 120 µm channels in silicon-substrate bonded to glass
- Pressure drop (Δh)
- Thermal Figure of Merit (TFM) constant

Visual Results

Compared Conclusion

- In general investigations with changing T_sat and heat flux showed shifting trends of the heat transfer coefficient h₁ suggesting a shift of the dominating boiling mechanism from high T_sat to low T_sat.
- Different boiling mechanisms are due to different bubble dynamics in the channels which can cause different pressure drop and heat transfer coefficient results.
- The Thermal Figure of Merit of the tested micro-channels is ~3 for the entire test range, which is a factor 4 better than the best performing conventional detector cooling method.
- The qualitative observations from the high-speed visualizations on micro-channels provide a consistent key of interpretation of the quantitative measurements.

The examples show that T_sat greatly affects the boiling properties of CO₂ in small channels and that new advanced models based on this new findings can enhance the design optimization of future mini- and micro-channel evaporators.

For more information some videos will be shown on a portable at the poster sessions!