Evaporative CO_2 pressure drops: comparison between measurements and calculations

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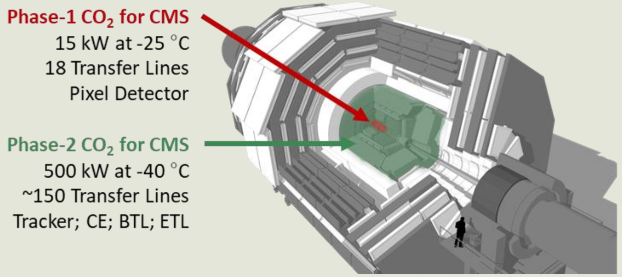
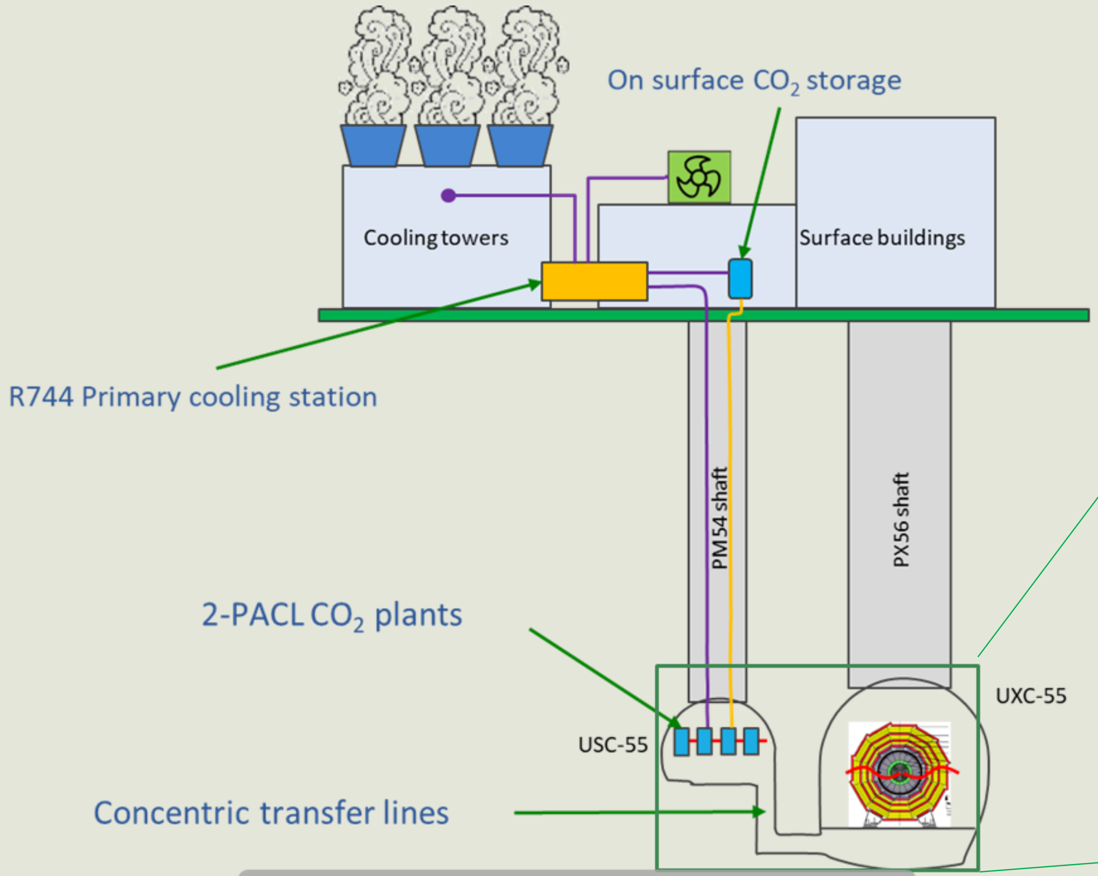
Outline

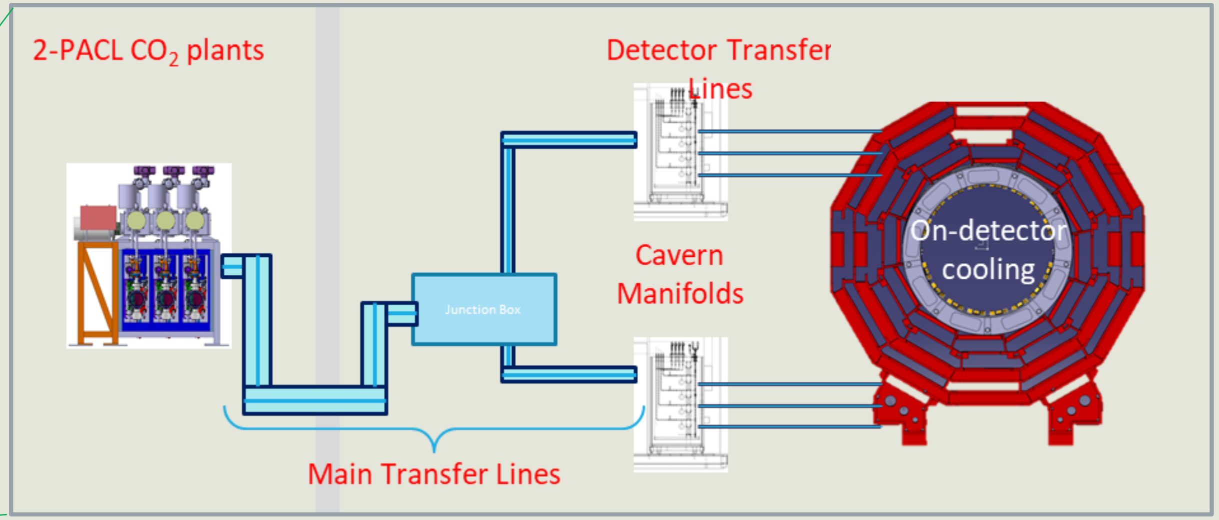
- Introduction
- Overview on CO_2 calculator tools
- Experimental setup
- Comparison between results
- Discussion
- Conclusion

Introduction – Phase 2 CO_2 for CMS





Phase-2 CMS CO_2 Cooling Schematic | J. Daguin



Introduction – Why CO_2 as refrigerant?

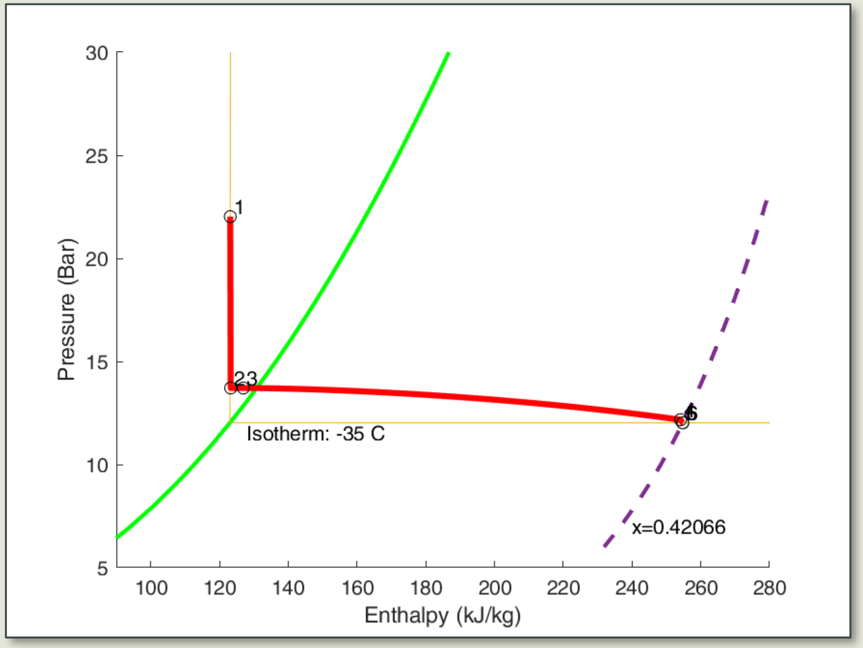
- Carbon Dioxide is selected as principal candidate for the present and next generations of silicon pixel detectors. Respect to traditional refrigeration fluids CO_2 in general exhibits:
  - Higher saturation pressures,
  - Higher vapour density and lower liquid to vapour density ratio,
  - Higher liquid thermal conductivity,
  - Lower liquid viscosity
  - Lower surface tension
  - Environmental friendly

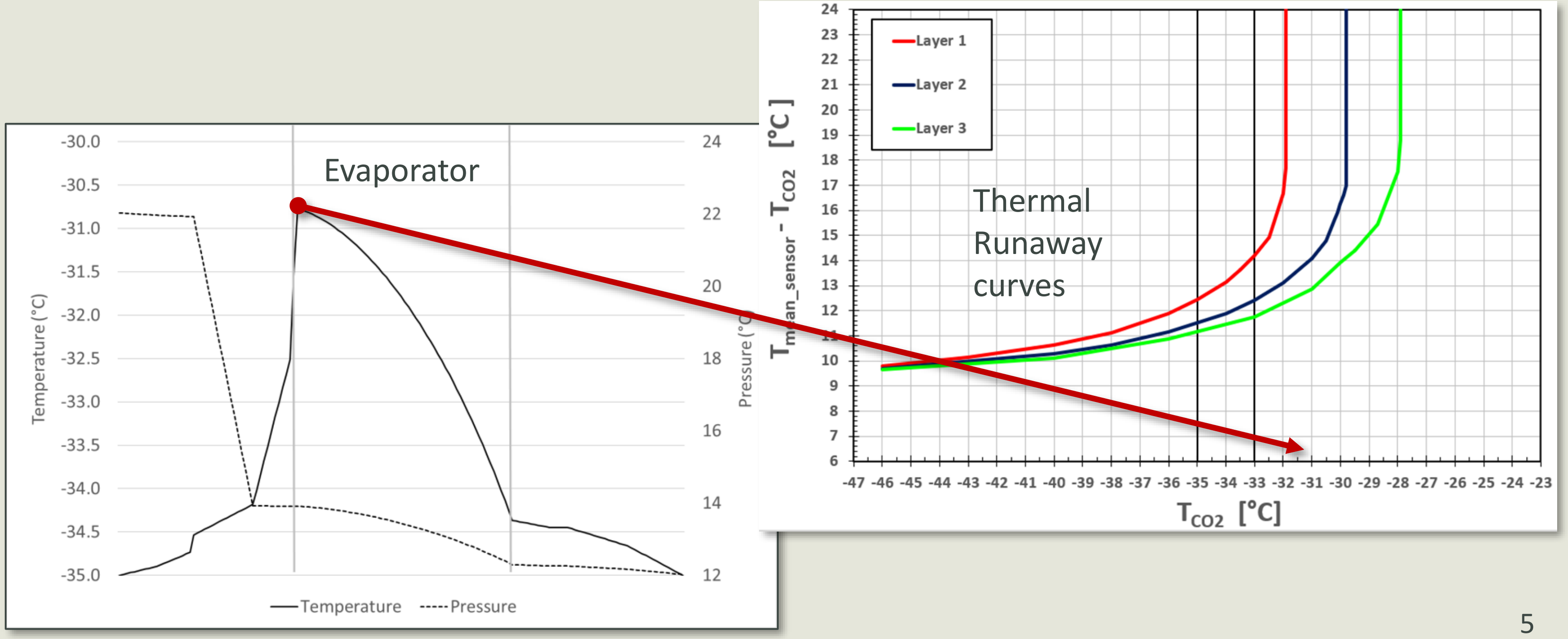
Small diameters of the pipe allowed

- These characteristics lead to have, in general, higher heat transfer coefficients and lower pressure drop along the evaporator for the CO_2 respect to conventional refrigerants
- These properties are function of the saturation temperature

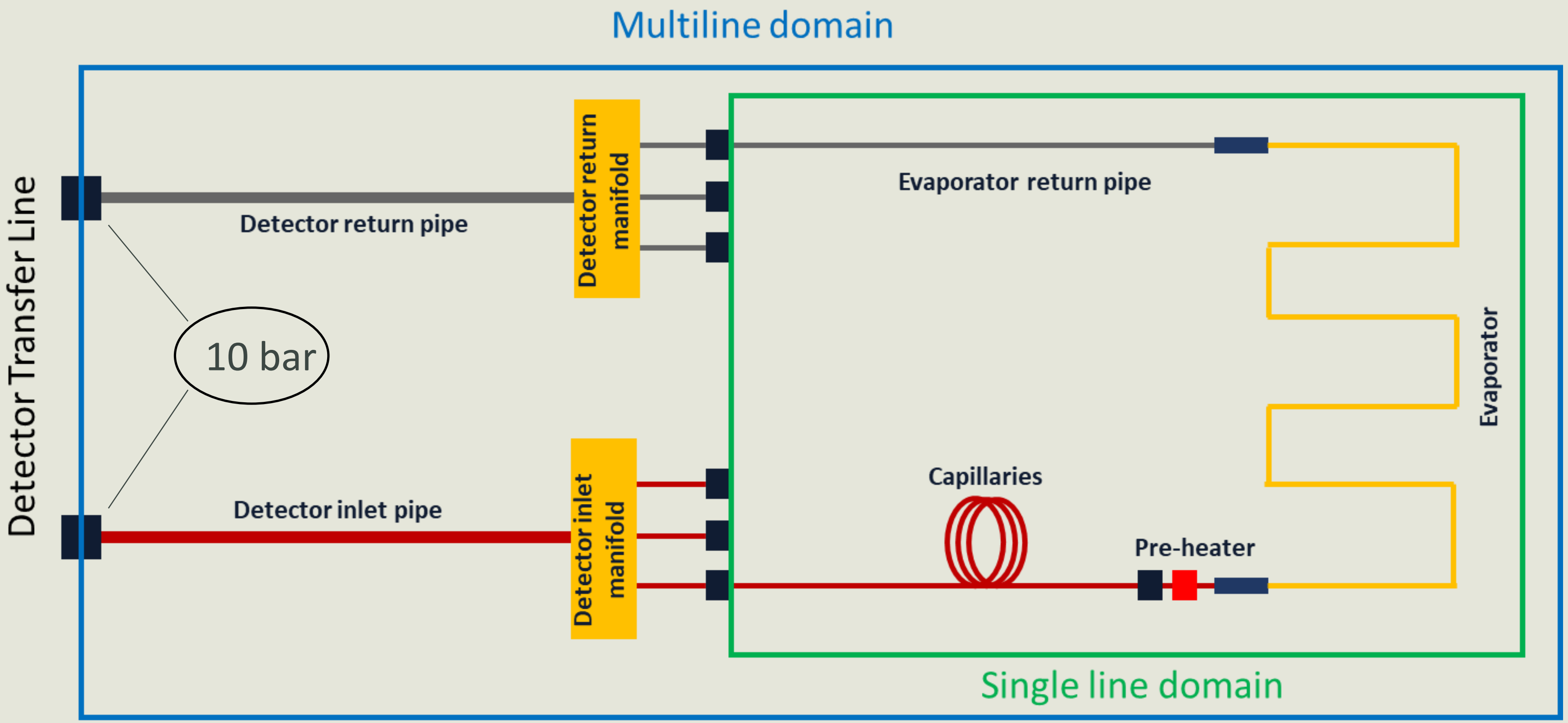
Introduction – Pressure drop

- 2 Phase Accumulator Controlled Loop is the robust technology used for precisely controlling the evaporator in the detector cooling loop
- The pressure drop inside the evaporator plays a fundamental role to avoid liquid phase and too high temperatures under the first modules





Overview on CO_2 calculator tools



The real engine of both tools is CoBra developed by NIKHEF to describe the complex behaviour of two-phase CO_2

MATLAB calculator tools

- Single line tool
  - ID capillaries diameter sizing
  - Performance of single evaporator (pressure drop, temperature profile, vapour quality, …)
- Multiline tool
  - Refinement of the capillary lengths
  - Overall checking on the detector system performance (pressure drop, temperature profile, vapour quality, balancing of the flow between branches, …)

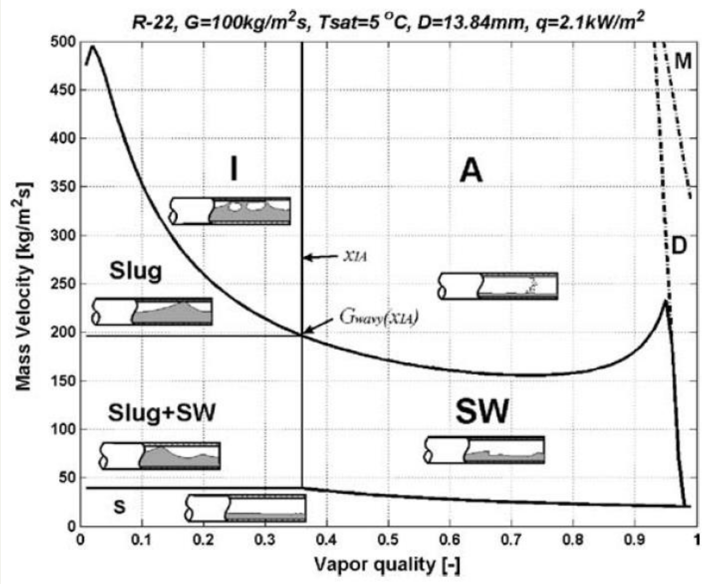
Overview on CO_2 calculator tools – pressure drop correlations

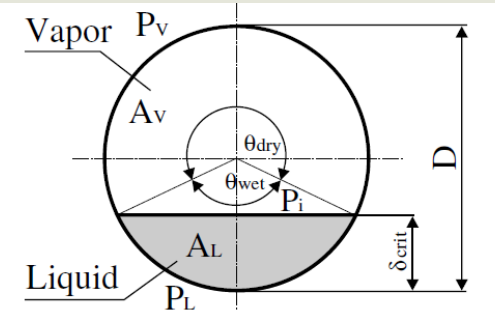
(Cheng–Ribatski–Wojtan) Thome Pressure Drop Correlation

- The correlation is flow pattern based model of two-phase frictional pressure drop for CO_2.

- The flow pattern model treats each flow regime separately and then insures a smooth transition at the transition boundary, in agreement with the experimental observations.

- The flow pattern map is applicable to well defined conditions:
  - Tube diameters from 0.6 to 10 mm,
  - Mass velocities from 50 to 1500 kg/m² s,
  - Specific heat fluxes from 1.8 to 46 kW/m² and
  - Saturation temperatures from - 28 to +25 °C





L. Cheng, G. Ribatski, J.M. Quibén, J.R. Thome, **New prediction methods for CO2 evaporation inside tubes: Part I –A two-phase flow pattern map and a flow pattern based phenomenological model for two-phase flow frictional pressure drops**, Int. J. Heat Mass Transf. 51 (1) (2008) 111–124, doi: 10.1016/j. ijheatmasstransfer.20 07.04.0 02 .

Overview on CO_2 calculator tools – pressure drop correlations

Friedel Pressure Drop Correlation

- The correlation of Friedel considers the liquid phase flowing alone in the channel. The pressure drop of the liquid phase is increased by a multiplier to take into account the two-phase regime.

- The multiplier is given as a function of the vapor quality, the density and viscosity ratios and dimensionless numbers.

$$\left(\frac{dP}{dZ}\right)_f = \left(\frac{dP}{dZ}\right)_{lo} \varphi_{lo}^2 \,,\; \varphi_{lo}^2 = E + \frac{3.24\,F\,H}{Fr^{0.045}\,We^{0.035}} \,,\; \left(\frac{dP}{dZ}\right)_{lo} = \frac{2 f_{lo} G^2}{D \rho_l}$$

$$E = (1-x)^2 + x^2 \left(\frac{\rho_l}{\rho_g}\right)\left(\frac{f_{go}}{f_{lo}}\right) ,\; F = x^{0.78}(1-x)^{0.224} ,\; H = \left(\frac{\rho_l}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_l}\right)^{0.19}\left(1-\frac{\mu_g}{\mu_l}\right)^{0.7}$$

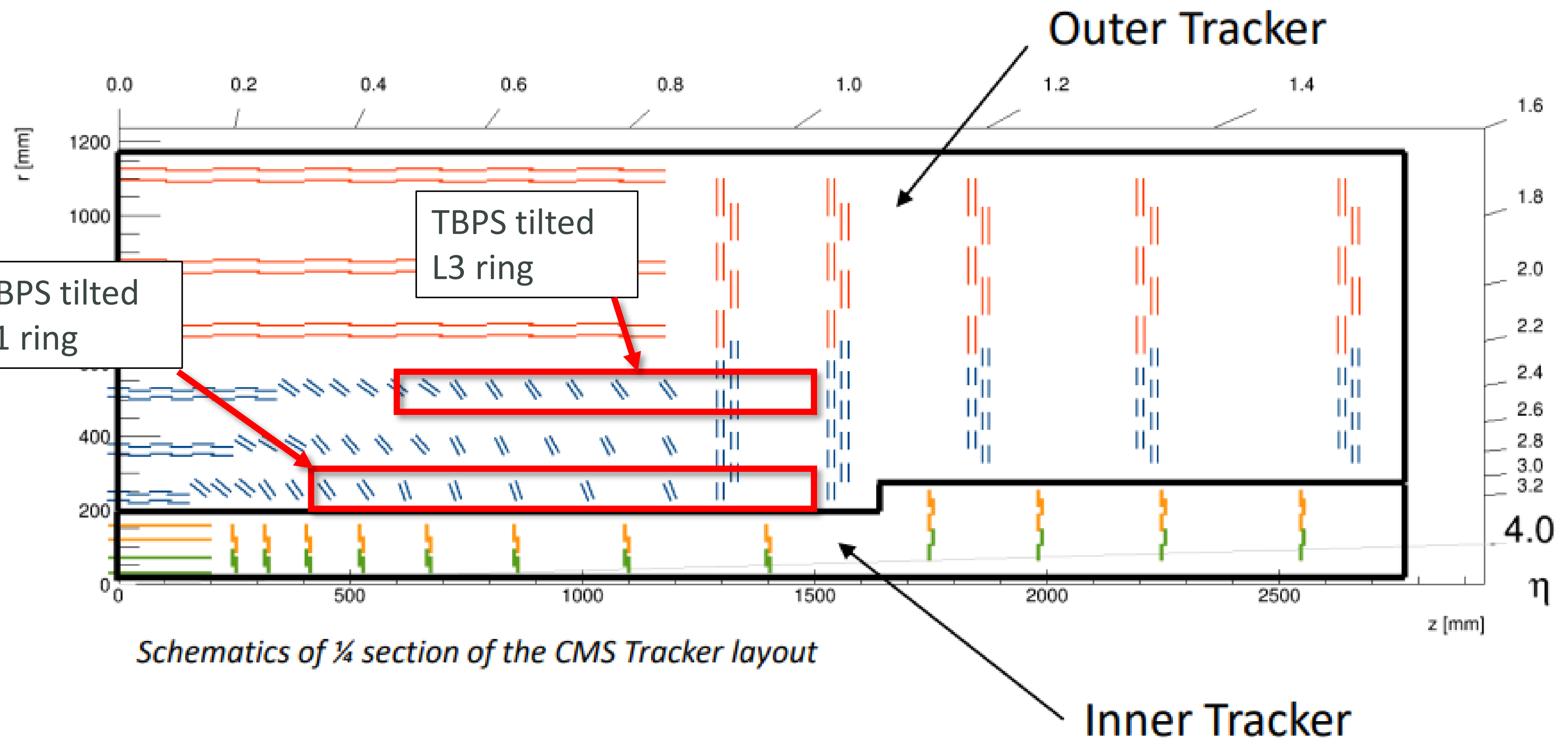
$$Fr = \frac{G^2}{g\,D\,\rho_h^2} ,\; We = \frac{G^2\,D}{\sigma\,\rho_h} ,\; \rho_h = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1}$$

$$f_{lo} = \frac{16}{Re_{lo}} \; for\; Re_{lo} < 2000 ,\; f_{lo} = \frac{0.0791}{Re_{lo}^{0.025}} \; for\; Re_{lo} > 2000 ,\; Re_{lo} = \frac{GD}{\mu_l}$$

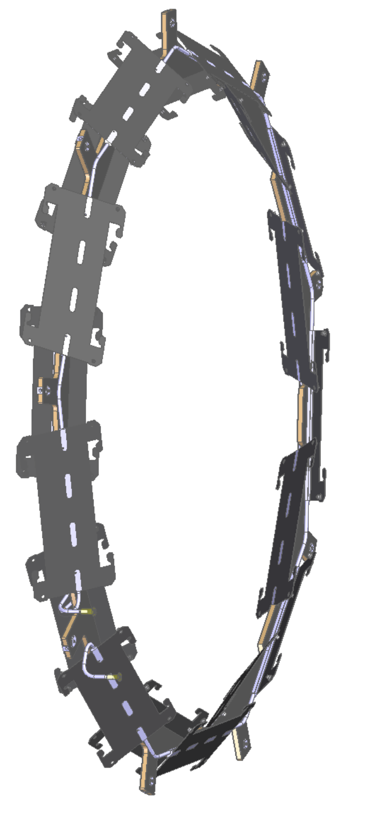
$$f_{go} = \frac{16}{Re_{go}} \; for\; Re_{go} < 2000 ,\; f_{go} = \frac{0.0791}{Re_{go}^{0.25}} \; for\; Re_{go} > 2000 ,\; Re_{go} = \frac{GD}{\mu_g}$$

L. Friedel , **Improved friction pressure drop correlations for horizontal and vertical two-phase pipe flow**, in: Proceedings of the European Two-Phase Flow Group Meeting, 1979 .

Experimental test setup

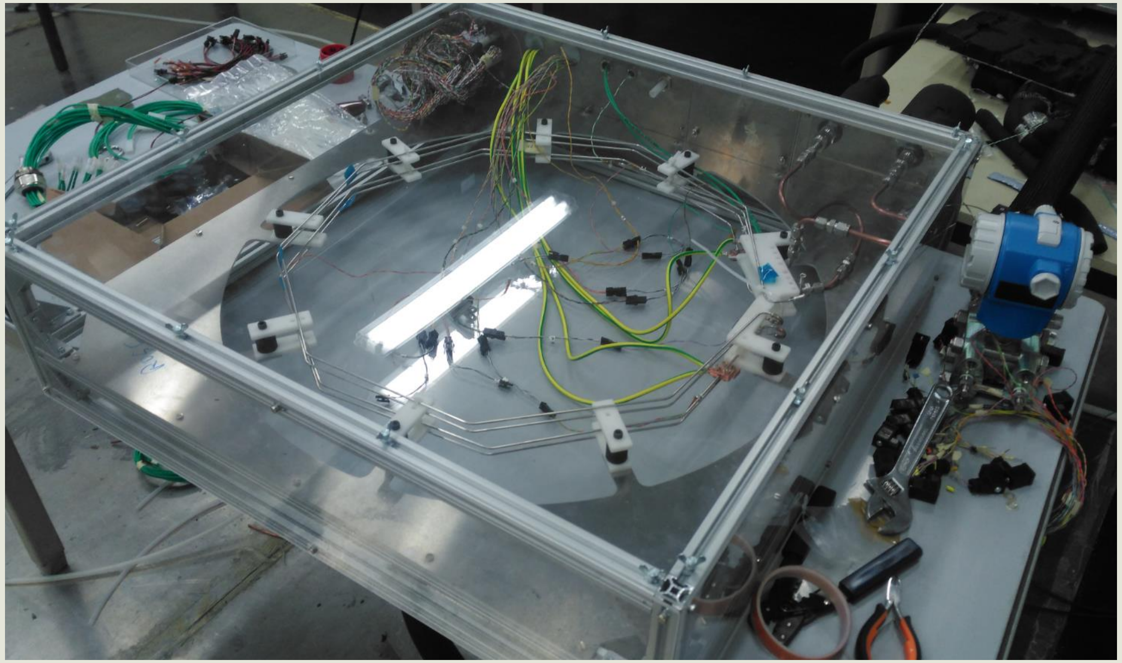


Schematics of ¼ section of the CMS Tracker layout



Experimental test setup

Tracker TBPS tilted Layer 1 and Layer 3



- L1 ring pipe heated resistively by applying a voltage to the centre.
- “L3 pipe” is simply two L1 rings in series, with the same setup.
- Differential pressure sensor added to measure the pressure drop through the circuit
- Evaporator pipe Inner Diameter 2.2 mm in stainless steel

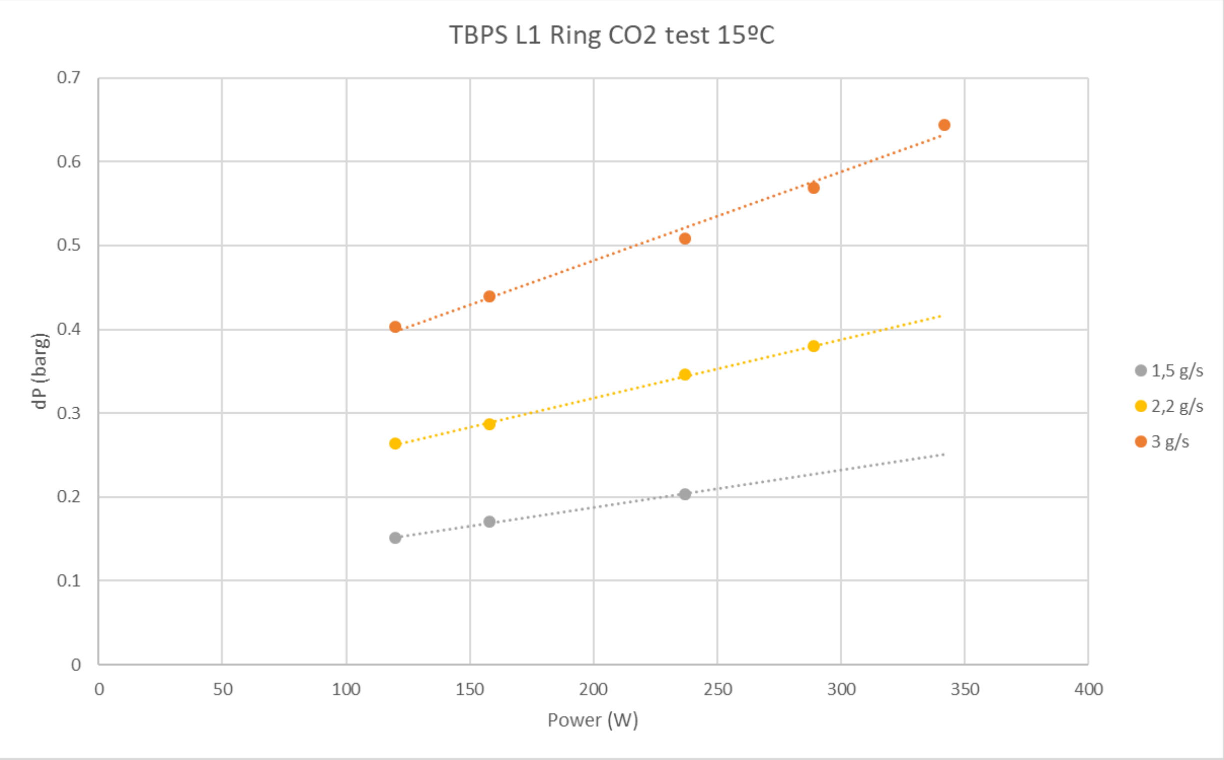
Test Parameters

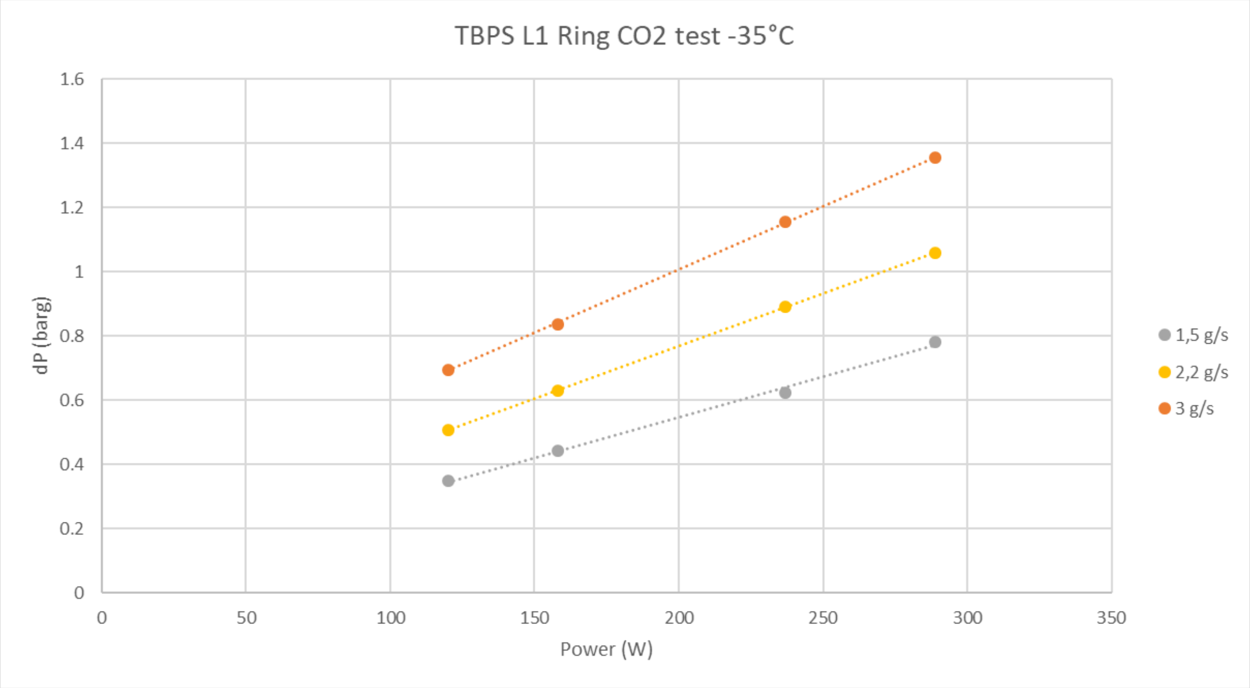
CO_2 Set Point	51bar (+15°C)	CO_2 Set Point	12bar (-35°C)
Dummy Load Power	100-400W	Dummy Load Power	100-400W
Flow	1.2-3.3g/s	Flow	1.2-3.3g/s
Room Temperature	+15°C +/-1°C	Room Temperature	-34°C +/-1°C

Experimental test setup

Tracker TBPS Layer 1 and Layer 3

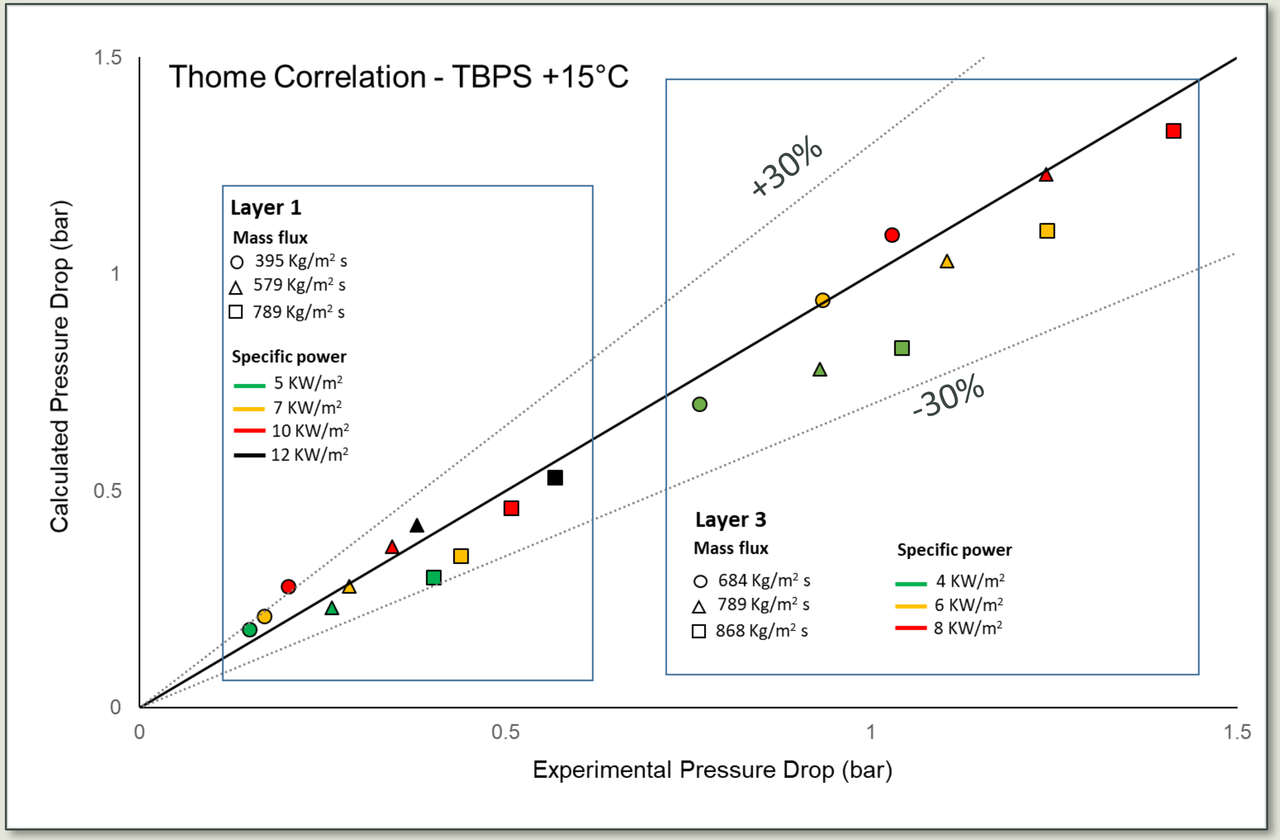
Experimental results for L1 ring at +15°C and -35°C

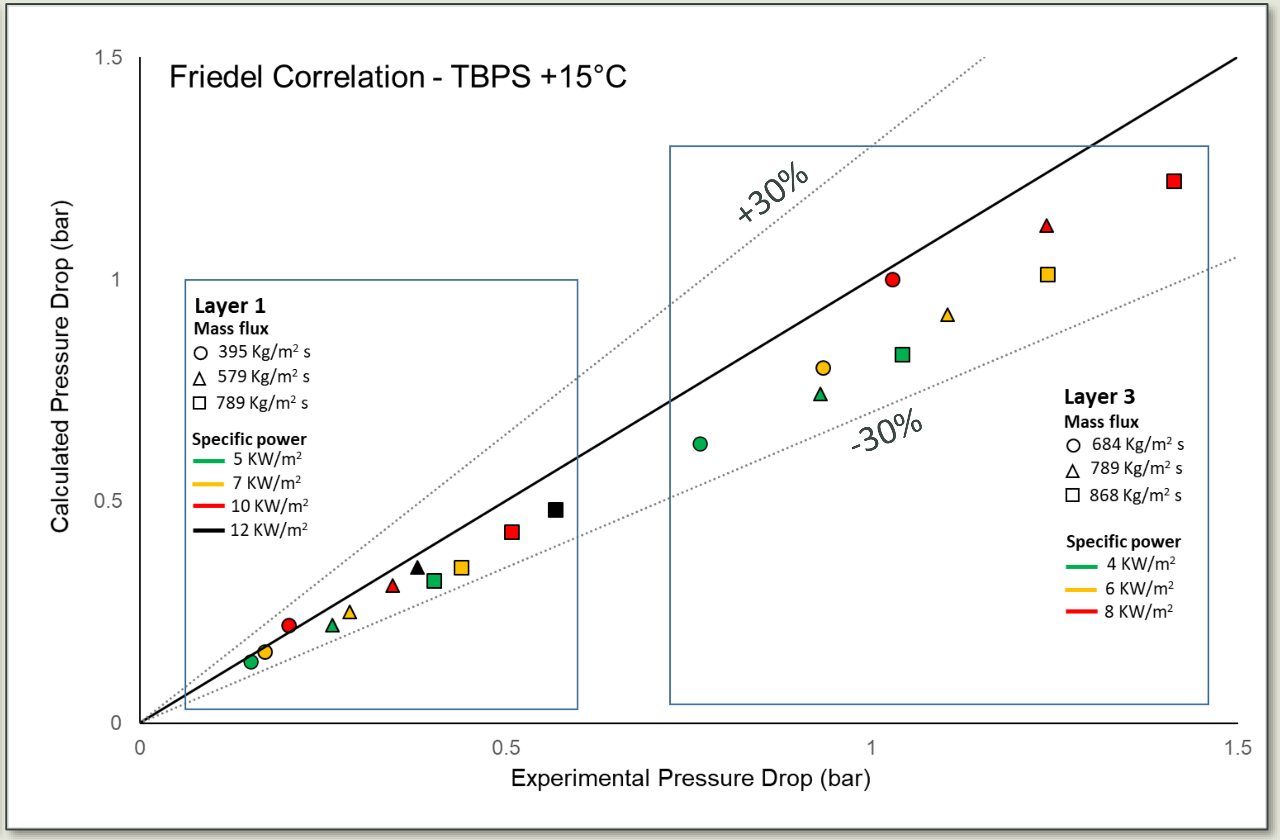




Results – Comparison between experimental and calculation approaches

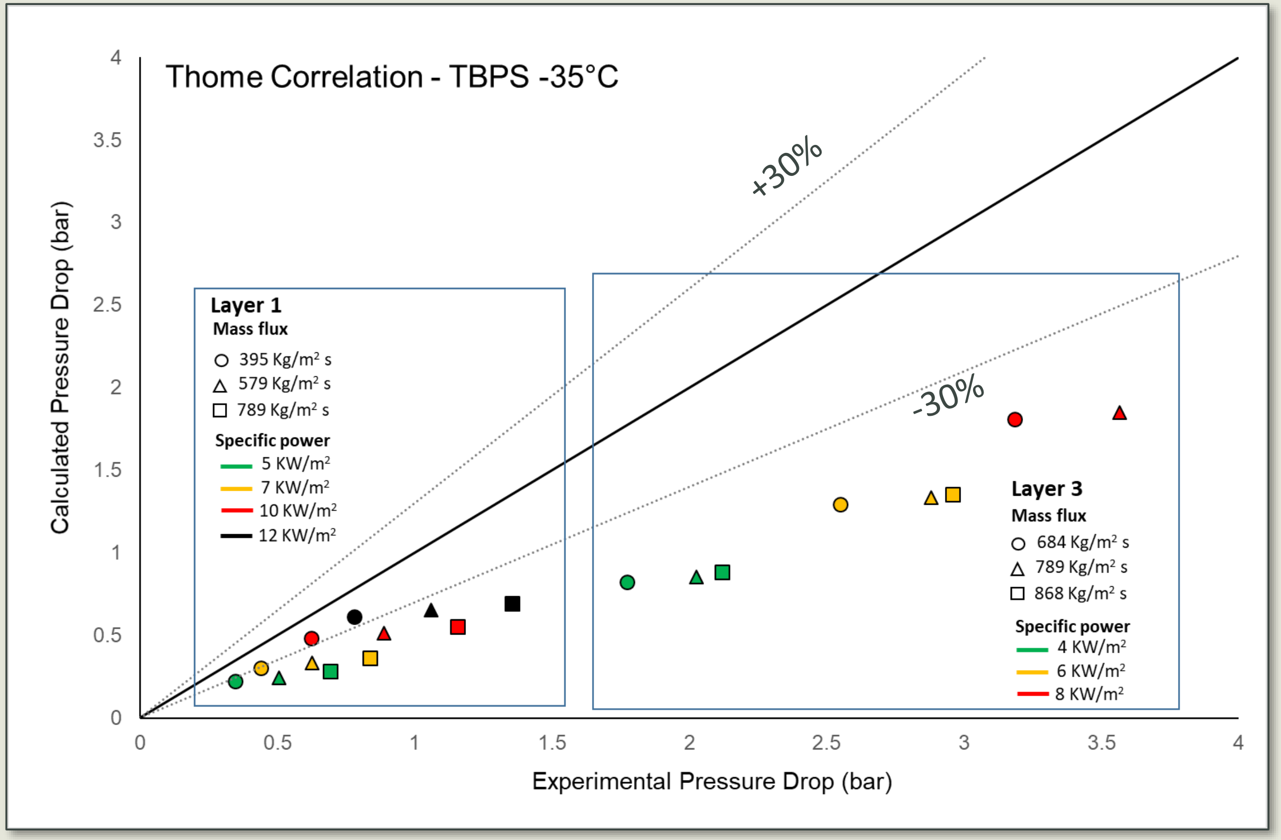
Saturation temperature +15°C – pressure drop correlations Thome and Friedel

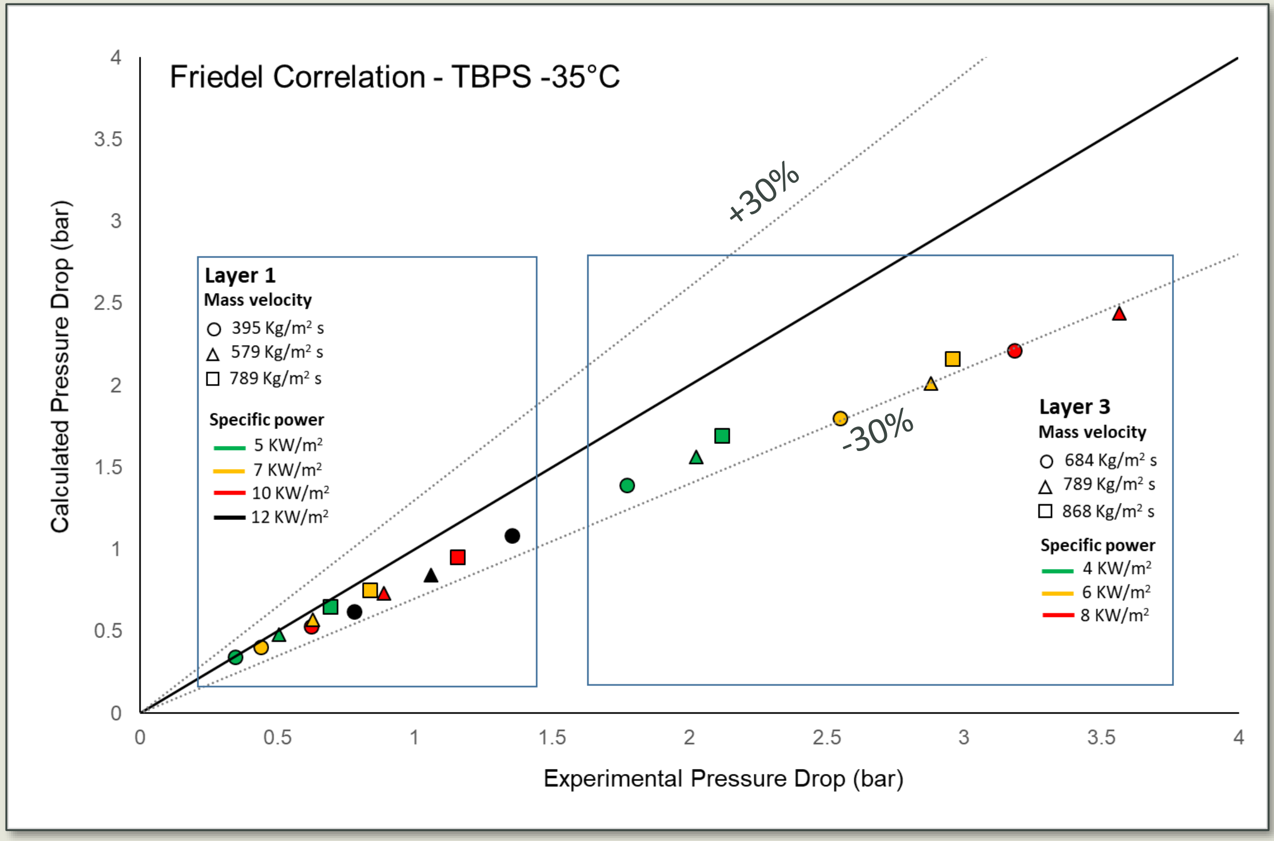




Results – Comparison between experimental and calculation approaches

Saturation temperature -35°C – pressure drop correlations Thome and Friedel





Discussion

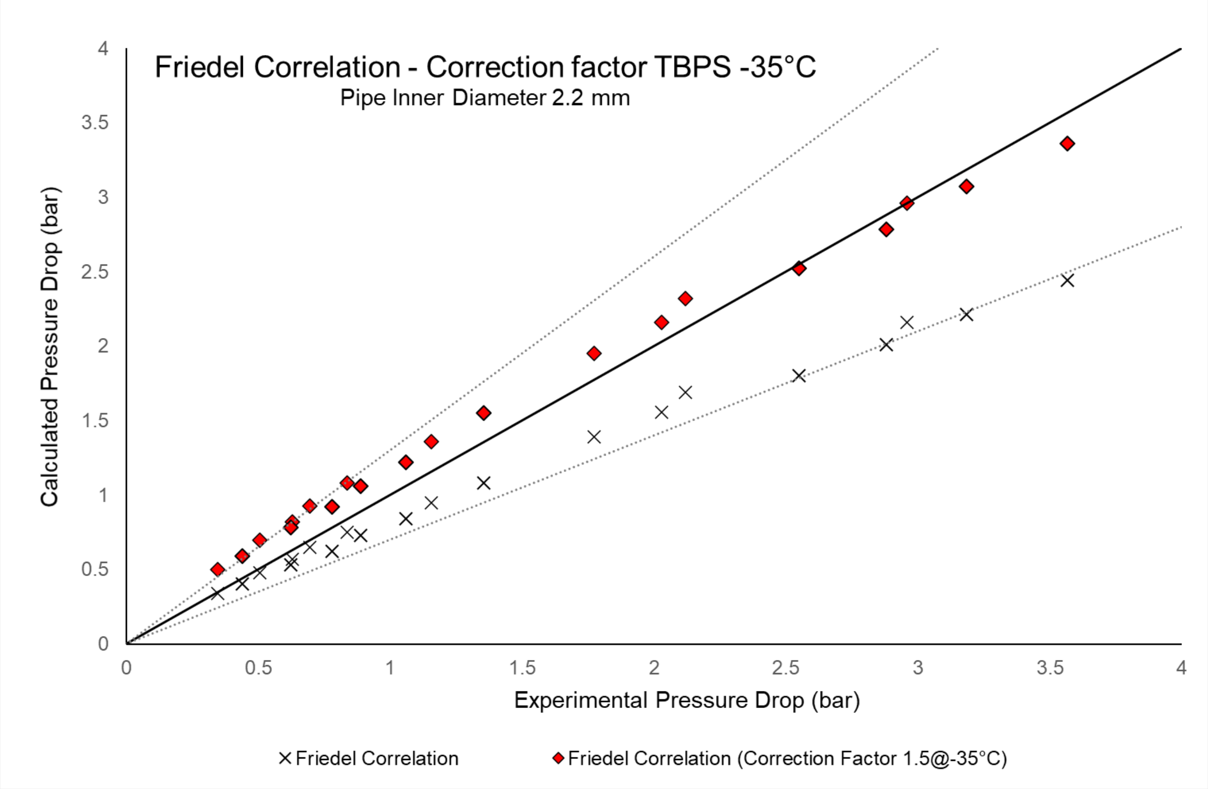
- The predicted pressure drops from the correlations of Thome and Friedel show a good agreement with measurement at saturation temperature equal to +15°C.
- Thome correlation seems strongly underestimate the pressure drop at saturation temperature equal to -35°C. Friedel as well shows a less strong underestimation.

↓

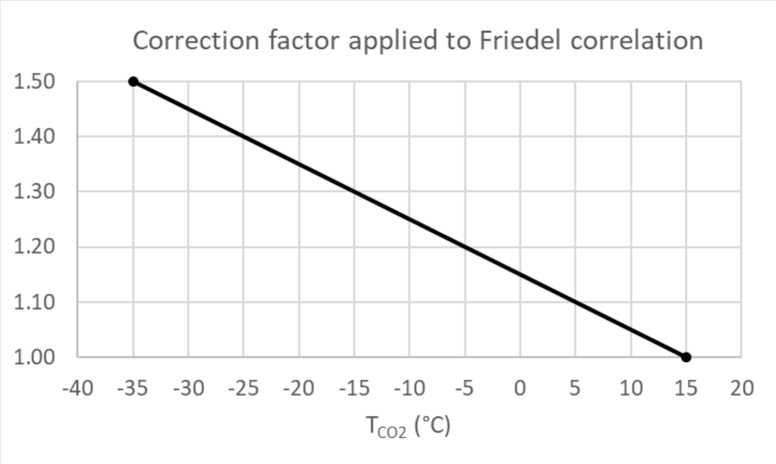
- In general, with decreasing of saturation temperature the difference between the vapour and liquid properties increases.
- Thus, generally from the correlations, the two-phase frictional pressure drop increases with decreasing of saturation temperature
- In addition, the surface tension is increasing with the decreasing of the saturation temperature. This leads to a larger bubble radius and to an increase of confinement number.

Discussion

Correction factor proposal



Friedel correlation predicts better than Thome correlation in cold operation (CO_2 @ -35°C).
A correction factor is applied for the design phase in the calculator tools. The factor is applied to Friedel correlation and it is a linear correction factor that makes unchanged the pressure drop in the warm condition (CO_2 @ +15°C) and increases 1.5 times the pressure drop at cold operation.



Conclusion

- A comparison between the predicted and measured pressure drop on the cooling circuits with CO_2 as two-phase refrigerant has been performed.
- Two different correlations were studied changing them in the CoBra engine tool for the CO_2 calculations.
- The experimental setup for TBPS tilted sub-detector for CMS phase-2 has been used for the validation of the prediction. The pipe diameter of the evaporator is equal 2.2 mm (inner diameter). These properties are function of the saturation temperature.
- The results showed the underestimations of both pressure drop correlations at saturation temperature of -35°C.
- The physical properties temperature dependence is the main reason for a good agreement of the correlation at +15°C and strong underestimation at -35°C.
- As first step, a correction factor for the cooling loop designing has been applied to the calculation.

Thank you!

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CMS Compact Muon Solenoid

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