CO\textsubscript{2} based two phase cooling test set up for CMS trackers: Comparison of experiments with theoretical models

Abstract

CO\textsubscript{2} is radiation hard and has excellent thermodynamic properties for cooling in micro channels. The layer 1 of the pixel detector dissipates 144 W over a cooling pipe length of 5.5 m, diameter of 1.4 mm and thickness 50 microns. So the detector tube used in the test at Building 187 is a micro channel. The saturation temperature is -20°C, -10°C, the mass velocities vary from 325 kg/m\textsuperscript{2}s (0.5 g/s) to 1299 kg/m\textsuperscript{2}s (2 g/s), the heat fluxes vary from 1.595 kW/m\textsuperscript{2} (39 W) to 9.338 kW/m\textsuperscript{2} (226 W) in the tests. Cheng-Ribatski-Quiben-Thome correlation (2008) [44], being the most updated flow pattern map based method, was chosen for predicting the pressure drop over the detector tube. Friedel correlation (1979) [7] is an extensively tested separated flow model which is also chosen for the purpose of comparison. The flow pattern map predicts intermittent to annular flow transition for most of the tests and bubbly to annular transition for some of the low vapor quality and high mass velocities test. Cheng-Ribatski-Quiben-Thome correlation (2008) [44] predicts 80 % and the Friedel correlation (1979) [7] predicts 50 % of the valid test results within a deviation of 30 % for pressure drop over the detector tube.

Introduction
CMS stands for Compact Muon Solenoid. It is called so because it is small for its enormous weight, it detects muon and it has a coil inside its huge superconducting magnet. The detector is like a giant filter, where each layer is designed to stop, track or measure a different type of particle emerging from proton-proton and heavy ion collisions [1]. Particles emerging from collisions first meet a tracker, made entirely of silicon that charts their positions as they move through the detector and measures their momentum. Outside the tracker are calorimeters that measure the energy of particles. The tracker is made entirely of silicon. The tracker consists of the pixels, at the very core of the detector, which deals with the highest intensity of particles and the silicon micro strip detectors that surround it. Because there are 65 million channels, the power for each pixel must be kept to a minimum. Even with each only generating around 50 microwatts, the total power output is around the same as the energy produced by a hot plate. So as not to overheat the detector, the pixels are mounted on cooling tubes. [Fig 1] and [Fig 2] provide a clear illustration of the CMS detector.

![Figure 1 The set up of the CMS.](image-url)
CO$_2$ cooling such as for instance implemented in the LHCb VELO detector [2] could be an interesting solution for CMS Pixel cooling. LHCb has chosen CO$_2$, because it is radiation hard and has excellent thermodynamic properties for micro-channels. Intuitively, higher pressures seem a disadvantage but gas flow at higher pressures needs smaller pipe diameters, pressure drops due to flow become less significant, allowing smaller pipes and small pipes can easily support the required pressures. Present C$_6$F$_{14}$ single-phase coolant uses parallel cooling pipes with manifold and large cross-section silicon hoses for feed and drain in front of FPIX tracking region. New CO$_2$ allows serialized pipes without pressure drop problems and therefore reduces resident cooling liquid by large factor. At present everything indicates that this cooling method is feasible. A simple test setup is expected to increase the confidence level and show that the concept is correct. More sophisticated research is important to assure a full understanding of the system and optimize the design details as well as the operating parameters. The test set up is briefly described in the following section.

The aim of this project is to implement the most recent flow pattern based two phase pressure drop model proposed exclusively for CO$_2$ by Cheng-Ribatski-Quiben-Thome (2008) [44] and to compare the predicted pressure drop with that of the experimental pressure drop across the horizontal pipes using the software MATHCAD. The Friedel correlation (1979) [7] for two phase fluid flow has also been compared with test results. The test output is collected using
LABVIEW. The fluid properties used in the theoretical model and tests are obtained from REFPROP-NIST.

**Experiment**

The experimental set up [fig 3, 4, 5] was already in place when I joined the lab. The preferred cooling liquid temperature during operation is around -12 °C, which corresponds to a pressure of 25 bars. The pixel barrel cooling tube is specified as ID=1.4 mm, wall thickness 50 microns. Layer 1 of the pixel detector dissipates 144 W over a cooling pipe length of 5.5 m. In order to avoid heat transfer to the environment, which greatly complicates the interpretation of the measurement data, the detector pipe is located inside a freezer. Only temperature measurements along the tube are required since the pressure in a boiling liquid is very well indicated by the temperature. The schematic diagram of the experimental set up is shown in [fig 6]. The details related to the experiment can be obtained from [2]. By measuring the temperature with the help of PT100 temperature sensors along the detector tube the pressure drop over its length is determined. The tests are conducted under different conditions of heating, mass velocities and saturation temperature [Table 1]. The pressure enthalpy diagram [fig 7] for CO₂ is used extensively to determine various test parameters. The test data is collected with the help of LABVIEW [fig 8].

![Figure 3 Test set up consisting of the test rack, freezer, power and the data acquisition system.](image)
Figure 4 The test rack.

Figure 5 The detector tube along with the temperature sensors attached to the insulator.
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Figure 6 Schematic representation of the CO₂ cooling test set up.

Figure 7 The pressure enthalpy diagram showing a standard process path used in the tests.
The total pressure drop across a tube is the sum of the momentum pressure drop, frictional pressure drop and static pressure drop. The static pressure drop is zero for horizontal tubes. The
frictional pressure drop and the momentum pressure drop are calculated in different models accordingly.

The homogenous flow model is a convenient way of representing the two phase pressure drop. The liquid and vapor properties have been suitable averaged with the help of homogenous void fraction and vapor quality in such a way that it obeys the conventional equations for single phase fluid. The homogenous void fraction is calculated with the help of velocities and density of the liquid and gas phase along with the vapor qualities. The average density of the two phases is calculated using this homogenous void fraction and vapor quality.

However separated flow models for flows inside plane tubes give better predictions. In this model the two phases are considered to be flowing as two separate streams and this separation is represented with the help of void fraction. The void fraction is calculated with help of liquid and vapor density along with the total mass velocity. The momentum pressure drop is calculated as a function of mass velocity, void fraction, liquid and vapor density. The frictional pressure drop is calculated using the separated flow model. The earliest separated flow model was proposed by Lockhart Martinelli (1949) [3] and followed by Bankhoff (1960) [4], Grönerrud (1972) [5], Chrisholm (1973) [6], Friedel (1979) [7], Müller-Steinghagen-Heck (1986) [8]. In all these models they have used different two phase multipliers for their own experiment results. However with the inclusion of greater ranges of mass velocity and pipe diameter the applicability of most of the correlation is greatly reduced.

The respective distribution of the liquid and vapor phases in the flow channel leads to commonly observed flow structures, defined as two-phase flow patterns [fig 9] that have particular identifying characteristics. Boiling and condensation heat transfer coefficient, pressure drop, void fraction calculations are closely related and differ based on the two phase flow pattern.

Some of the earliest flow pattern maps for horizontal tubes were proposed by Baker (1954) [9], Taitel and Dukler (1976) [10]. Thome Et al. [10-16] have proposed a number of flow pattern based maps with substantial additions and improvements from time to time for flow boiling of a large number of fluids in which they have statistically analysed many data bases for different pipe diameters, mass velocities. In one of the flow pattern based pressure drop work proposed by Moreno Quibén-Thome (2007a, 2007b) [17, 18] for R-22, R-410A, R-134a they have observed that correlations proposed by Friedel(1979) [7], Muler-Steinhagen-Heck (1986) [8] are some of the best suited separated flow model based prediction. Ribastki-Woltzan-Thome (2006) [19] had
performed a review in which they had analysed various proposed pressure drop and heat transfer prediction models with experimental results covering many fluids and experimental conditions. It has been observed that, most of the models are specific to their own experiment database for which there is a constant effort to test the old models with new experimental parameters such as different fluids at new mass velocities and pipe diameter. The recent models with their improvements over the older ones can satisfy a wide variety of experimental parameters. However it has been recommended by Thome in [20] to test the existing models with any new experimental results before drawing conclusions. A detailed analysis of most of the models by various researchers and a brief review of flow pattern maps and various pressure drop models can be obtained from the Wolverine data book [20].

CO₂ is used in low temperature refrigeration systems and heat pumps. It is radiation hard and environment friendly as compared to the chloro-floro-carbon. CO₂ has low critical temperature 31.1 °C and high critical pressure of 73.8 bars for which it can operate at high working pressure thus leading to low pressure drops. As a result it has a higher flow boiling heat transfer coefficient as compared to conventional refrigerants. At the same time the dry out and mist region commences much earlier in CO₂ as compared to conventional refrigerants. Hence simple extrapolation of existing theoretical correlations for calculating flow pattern maps, pressure drop and heat transfer coefficients meant for other refrigerants to CO₂ can lead to erroneous results [20, 21].

In order to differentiate micro channels from macro channels, 3mm diameter proposed by [22] has been accepted as the threshold for micro channels. Many researchers have performed experiments [23-38] with CO₂ on micro channels. Yun-Kim (2004) [39] proposed a flow pattern map for annular, bubbly and slug flow based on their observations. Thome-El Hajal had proposed a flow pattern map for CO₂ (2002) [40] and flow pattern based boiling heat transfer prediction in (2004) [41]. Thome-Ribatski (2005) [21] in their state-of-the-art review for CO₂ in macro channels and micro channels had suggested the need for better prediction of CO₂ data for micro channels and expansion of the Thome-El Hajal (2002, 2004) [40, 41] flow pattern based predictions to dryout region. Cheng-Ribatski-wotzan-Thome (2006) [42, 43] devised a new flow pattern map and heat transfer coefficient prediction method, by bringing changes to the Thome-
El Hajal [40, 41], in which they have made changes to the prediction methods used in the dry out region in their flow pattern map and hence in the heat transfer coefficient.

The most recent, updated and tested two phase flow pattern based pressure drop and heat transfer coefficient prediction has been developed by Cheng-Ribatski-Quiben-Thome (2008) [44, 45]. The method includes a new annular to dry out transition and dry out to mist transition. It also includes a new bubbly region which occurs at low vapor quality and high mass velocities. The updated map is applicable to a wider range of conditions: tube diameters from 0.6 to 10 mm, mass velocities from 50 to 1500 kg/m$^2$s, heat fluxes from 1.8 to 46 kW/m$^2$ and saturation temperatures from -28 to +25 °C (reduced pressures from 0.21 to 0.87). This method has been used to simulate the performance of CO$_2$ in a silicon multi-micro channel evaporator for cooling microprocessors by Cheng-Thome (2009) [46].

Since the diameter of the detector tube used in the experiment is 1.4 mm so it is a case of micro channel. As observed from table 1, the saturation temperature is -20 °C, -10 °C, the mass velocities vary from 325 kg/m$^2$s (0.5 g/s) to 1299 kg/m$^2$s (2 g/s), the heat fluxes vary from 1.595 kW/m$^2$ (39 W) to 9.338 kW/m$^2$ (226 W). Hence the Cheng-Ribatski-Quiben-Thome (2008) [44] based flow pattern based pressure drop prediction method is used for comparing the experimental results. The flow pattern cannot be observed in the present test set up as there is no provision for any such device but the knowledge of the flow pattern can be useful in understanding the variation of heat transfer coefficient in the detector tube. This necessitates the use of theoretical flow pattern maps to observe the flow patterns inside the detector tubes.

![Figure 9 Different flow patterns in horizontal tubes.](image-url)
Figure 10 Variation of temperature with time for all the temperature sensors present at different positions of the detector tube.

Discussion

[Fig 10] illustrates the direct output from one of the tests. This data is further analyzed for each test with the help of theoretical models. The calculations involved in this project work were performed using Mathcad. Mathcad is engineering software primarily used for documentation and re-use of engineering calculations marketed by Parametric Technology Corporation (PTC).

The flow pattern map gives the type of flow pattern that exists in the pipe for a given condition of vapor quality and flow rate. Flow pattern maps [fig 11, fig 12] are plotted for all the tests and the path of each test based on the change in vapor quality is studied. [Fig 11] and [fig 12] represents the set of flow pattern maps for two different conditions of temperature -20°C and -10°C respectively. The flow pattern map for each experiment changes due to the change in heat flux. The mist region becomes prominent with the increase in heat flux. All the experiments are expected to show an intermittent to annular transition except [fig 11.7, fig 11.9, fig 11.10, fig 12.8, fig 12.10, fig 12.11] which show an intermittent to bubbly transition when the heat flux and mass velocity are greater than 4586 W/m² (111 W) and 974 kg/m²s (1.5 g/s) respectively. [Table 2] and [Table 3] gives a summary of the observations related to flow pattern.
Figure 11.1 \(T_s=-20^\circ C \ | X_{in}=6\% \ | P=39W \ q=1611W/m^2 \ | \dot{m}=.75g/s \ M=487 \ kg/m^2s\)

Figure 11.2 \(T_s=-20^\circ C \ | X_{in}=6\% \ | P=39W \ q=1611W/m^2 \ | \dot{m}=.75g/s \ M=487 \ kg/m^2s\)

Figure 11.3 \(T_s=-20^\circ C \ | X_{in}=11\% \ | P=80W \ q=3305W/m^2 \ | \dot{m}=.5g/s \ M=325 \ kg/m^2s\)
Figure 11.4 $T_s=-20^\circ C$ | $X_{in}=5\%$ | $P=75W$ $q=3099W/m^2$ | $\dot{m}=0.75g/s$ $M=487kg/m^2s$

Figure 11.5 $T_s=-20^\circ C$ | $X_{in}=4\%$ | $P=75W$ $q=3099W/m^2$ | $\dot{m}=1g/s$ $M=650kg/m^2s$

Figure 11.6 $T_s=-20^\circ C$ | $X_{in}=3\%$ | $P=111W$ $q=4586W/m^2$ | $\dot{m}=1g/s$ $M=650 kg/m^2 s$
Figure 11.7 $T_s = -20^\circ C \mid X_{in} = 2\% \mid P = 111 W \ q = 4586 W/m^2 \mid \dot{m} = 1.5 g/s \ M = 974 kg/m^2s$

Figure 11.8 $T_s = -20^\circ C \mid X_{in} = 2\% \mid P = 150 W \ q = 6198 W/m^2 \mid \dot{m} = 1 g/s \ M = 650 kg/m^2s$

Figure 11.9 $T_s = -20^\circ C \mid X_{in} = 0\% \mid P = 150 W \ q = 6198 W/m^2 \mid \dot{m} = 1.5 g/s \ M = 974 kg/m^2s$
Figure 11.10 $T_s=-20^\circ C$ | $X_{in}=0\%$ | $P=222W$ | $q=9173W/m^2$ | $m=1.5g/s$ | $M=974kg/m^2s$

Figure 11 Flow pattern diagram showing the process path in the form of change in flow pattern for the given experimental condition at -20°C. 1: Stratified, 2: Stratified-Wavy-Slug, 3: Stratified-Wavy, 4: Intermittent, 5: Annular, 6: Dry out, 7: Mist, 8: Bubbly. The dots in the map indicate the experimental path in terms of change in vapor quality.

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Power [watts]</th>
<th>Mass Flow [g/s]</th>
<th>Inlet Vapor Quality [%]</th>
<th>Final vapour Quality [%]</th>
<th>Change in flow pattern</th>
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<td>1</td>
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<td>8.4</td>
<td>35.1</td>
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<td>23.8</td>
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</tr>
<tr>
<td>3</td>
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<td>0.5</td>
<td>11.4</td>
<td>67.3</td>
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<tr>
<td>4</td>
<td>74.8</td>
<td>0.75</td>
<td>4.8</td>
<td>39.7</td>
<td>I–A</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
<td>1</td>
<td>4</td>
<td>30.1</td>
<td>I–A</td>
</tr>
<tr>
<td>6</td>
<td>111.5</td>
<td>1</td>
<td>3.4</td>
<td>42.7</td>
<td>I–A</td>
</tr>
<tr>
<td>7</td>
<td>111.5</td>
<td>1.5</td>
<td>1.8</td>
<td>27.6</td>
<td>B–A</td>
</tr>
<tr>
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<td>150</td>
<td>1</td>
<td>2.4</td>
<td>53.9</td>
<td>I–A</td>
</tr>
<tr>
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<td>150</td>
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<tr>
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<td>1.5</td>
<td>0</td>
<td>50.8</td>
<td>B–A</td>
</tr>
</tbody>
</table>

Table 2 Vapor quality at inlet and outlet along with change in flow pattern for experiments performed at -20°C where I – Intermittent, A – Annular, B – Bubbly.
Figure 12.1 \( T_s = -10^\circ C \) | \( X_{in} = 6\% \) | \( P = 39W \) \( q = 1611W/m^2 \) | \( \dot{m} = 0.5g/s \) \( M = 325 \text{ kg/m}^2\text{s} \)

Figure 12.2 \( T_s = -10^\circ C \) | \( X_{in} = 6\% \) | \( P = 39W \) \( q = 1611W/m^2 \) | \( \dot{m} = 0.75g/s \) \( M = 487 \text{ kg/m}^2\text{s} \)

Figure 12.3 \( T_s = -10^\circ C \) | \( X_{in} = 6\% \) | \( P = 75W \) \( q = 3099 W/m^2 \) | \( \dot{m} = 0.5 g/s \) \( M = 325 \text{ kg/m}^2\text{s} \)
Figure 12.4 \( T_s = -10 \, ^\circ C \) | \( X_{in} = 4\% \) | \( P=75\, W \) \( q=3099\, W/m^2 \) | \( \dot{m}=0.75\, g/s \) \( M=487\, kg/m^2\, s \)

Figure 12.5 \( T_s = -10\, ^\circ C \) | \( X_{in} = 4\% \) | \( P=75\, W \) \( q=3099\, W/m^2 \) | \( \dot{m}=1\, g/s \) \( M=650\, kg/m^2\, s \)

Figure 12.6 \( T_s = -10\, ^\circ C \) | \( X_{in} = 7\% \) | \( P=111\, W \) \( q=4586\, W/m^2 \) | \( \dot{m}=0.75g/s \) \( M=487\, kg/m^2\, s \)
Figure 12.7 $T_s=-10^\circ C$ | $X_{in}=2\%$ | $P=111\text{W}$ $q=4586\text{W/m}^2$ | $\dot{m}=1\text{g/s}$ $M=650\text{kg/m}^2\text{s}$

Figure 12.8 $T_s=-10^\circ C$ | $X_{in}=1\%$ | $P=111\text{W}$ $q=4586\text{W/m}^2$ | $\dot{m}=1.5\text{g/s}$ $M=974\text{kg/m}^2\text{s}$

Figure 12.9 $T_s=-10^\circ C$ | $X_{in}=3\%$ | $P=150\text{W}$ $q=6198\text{W/m}^2$ | $\dot{m}=1\text{g/s}$ $M=650\text{kg/m}^2\text{s}$
Figure 12.10 $T_s = -10^\circ C \mid X_{in} = 34\% \mid P=150W \ q=6198\ W/m^2 \mid \dot{m}=1.5g/s \ M=974kg/m^2s$

Figure 12.11 $T_s = 10^\circ C \mid X_{in} = 0\% \mid P=226W \ q=9338W/m^2 \mid \dot{m}=2g/s \ M=1299kg/m^2s$

Figure 12 Flow pattern diagram showing the process path in the form of change in flow pattern for the given experimental condition at $-10^\circ C$. 1: Stratified, 2: Stratified-Wavy-Slug, 3: Stratified-Wavy, 4: Intermittent, 5: Annular, 6: Dry out, 7: Mist, 8: Bubbly. The dots in the map indicate the experimental path in terms of change in vapor quality.
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Table 3: Vapor quality at inlet and outlet along with change in flow pattern for experiments performed at -10°C where I – Intermittent, A – Annular, B – Bubbly.

The pressure and hence the temperature, according to the respective flow patterns, across the length of the tube is predicted using the correlations given by Cheng-Ribatski-Quiben-Thome correlation (2008) [44]. Similarly the pressure and hence the temperature predicted by Friedel correlation (1979) [7] is also obtained. Since, in the tests the eleven temperature sensors are used at fixed interval all along the detector tube, so the theoretical calculations, to find the pressure drop, are also performed over the ten sections to obtain the total pressure drop over the detector tube.

Table 4: Comparison of theoretical predictions with experimental results for experiments performed at -20°C.
Table 5 Comparison of theoretical predictions from experimental results for experiments performed at -10°C.

However the comparison of pressure drop over the sections of the detector tube shown in [fig 13, fig 14] gives some interesting results. Pressure drop is calculated as the difference between the initial and final pressure over the selected section. It is observed in [fig 13, fig 14] that the Friedel correlation (1979) [7] always predicts a higher pressure drop than the Cheng-Ribatski-Quiben-Thome correlation (2008) [44]. The theoretical pressure drop predictions along the length of the detector tube remains almost constant for low heat flux and low mass velocities tests where as with the increase in heat flux and mass velocity the pressure drop shows an increasing trend along the length of the detector tube. In other words, for the tests with high heat flux and mass velocity, the pressure drop is comparatively higher in the last section as compared to that of the first section of the detector tube. But it was found out that in many tests [fig 13.1, fig 13.2, fig 13.4, fig 13.5, fig 14.1, fig 14.2, fig 14.3, fig 14.4, fig 14.5, and fig 14.10] the pressure drop over certain section is negative. This anomaly is more prominent in the tests conducted at -10°C (6 tests) then -20°C (4 tests). These tests were conducted at low heat flux and mass velocity. Presence of moisture inside the freezer can be a factor for such results as a result of which flushing the freezer with dry air can be a potential solution. The present test set up (as of August 2009) is equipped with necessary modifications for dry air, so these failed tests can be conducted again to carry out the corrections in the database.
Figure 13.1 $T_s = -20^\circ$ C | $X_{in} = 8\%$ | $P = 38W$ $q = 1570W/m^2$ | $\dot{m} = .5 g/s$ $M = 325 kg/m^2 s$

Figure 13.2 $T_s = -20^\circ$ C | $X_{in} = 6\%$ | $P = 39W$ $q = 1611W/m^2$ | $\dot{m} = .75 g/s$ $M = 487 kg/m^2 s$

Figure 13.3 $T_s = -20^\circ$ C | $X_{in} = 11\%$ | $P = 80W$ $q = 3305W/m^2$ | $\dot{m} = .5g/s$ $M = 325 kg/m^2 s$
Figure 13.4 $T_s = -20^\circ C$ | $X_{in} = 5\%$ | $P = 75 W$ $q = 3099 W/m^2$ | $\dot{m} = 0.75 g/s$ $M = 487 kg/m^2s$

Figure 13.5 $T_s = -20^\circ C$ | $X_{in} = 4\%$ | $P = 75 W$ $q = 3099 W/m^2$ | $\dot{m} = 1 g/s$ $M = 650 kg/m^2s$

Figure 13.6 $T_s = -20^\circ C$ | $X_{in} = 3\%$ | $P = 111 W$ $q = 4586 W/m^2$ | $\dot{m} = 1 g/s$ $M = 650 kg/m^2s$
Figure 13.7 Ts=-20°C | X_{in}=2% | P=111W q=4586W/m² | m=1.5 g/s M=974kg/m²s

Figure 13.8 Ts=-20°C | X_{in}=2% | P=150W q=6198W/m² | m=1g/s M=650kg/m²s

Figure 13.9 Ts=-20 °C | X_{in}=0% | P=150W q=6198W/m² | m=1.5g/s M=974kg/m²s
Figure 13.10  $T_s=-20^\circ C$ | $X_{in}=0\%$ | $P=222W$ $q=9173W/m^2$ | $\dot{m}=1.5g/s$ $M=974kg/m^2s$

Figure 13 Comparison of the pressure drop inside the detector tube with respect to different sections of the detector tube in experiment to that of the predicted by Thome Et al. correlation and Friedel correlation for the given two experimental conditions at -20°C.

Figure 14.1  $T_s=-10^\circ C$ | $X_{in}=6\%$ | $P=39W$ $q=1611W/m^2$ | $\dot{m}=5g/s$ $M=325 kg/m^2s$
Figure 14.2 $T_s = -10 ^\circ C \mid X_{in} = 6\% \mid P=39W q=1611W/m^2 \mid \dot{m}=0.75g/s M=487kg/m^2s$

Figure 14.3 $T_s = -10 ^\circ C \mid X_{in} = 6\% \mid P=75W q=3099 W/m^2 \mid \dot{m}=0.5 g/s M=325 kg/m^2s$

Figure 14.4 $T_s = -10 ^\circ C \mid X_{in} = 4\% \mid P=75W q=3099 W/m^2 \mid \dot{m}=0.75g/s M=487 kg/m^2s$
Figure 14.5 $T_s = -10^\circ C \mid X_{in} = 4\% \mid P=75W \ q=3099 \ W/m^2 \mid \dot{m}=1 \ g/s \ M=650 \ kg/m^2s$

Figure 14.6 $T_s = -10^\circ C \mid X_{in} = 7\% \mid P=111W \ q=4586 \ W/m^2 \mid \dot{m}=1.75g/s \ M=487 \ kg/m^2s$

Figure 14.7 $T_s = -10^\circ C \mid X_{in} = 2\% \mid P=111W \ q=4586 \ W/m^2 \mid \dot{m}=1g/s \ M=650 \ kg/m^2s$
Figure 14.8 \( T_s = -10^\circ C \) \( | X_{in} = 1\% | P = 111W q = 4586W/m^2 | \dot{m} = 1.5g/s M = 974kg/m^2s \)

Figure 14.9 \( T_s = -10^\circ C \) \( | X_{in} = 3\% | P = 150W q = 6198W/m^2 | \dot{m} = 1g/s M = 650kg/m^2s \)

Figure 14.10 \( T_s = -10^\circ C \) \( | X_{in} = 34\% | P = 150W q = 6198 W/m^2 | \dot{m} = 1.5g/s M = 974kg/m^2s \)
Figure 14.11 \( T_s = -10^\circ C \) | \( X_{in} = 0\% \) | \( P = 226W \ q = 9338W/m^2 \) | \( \dot{m} = 2g/s \ M = 1299kg/m^2s \)

Figure 14 Comparison of the pressure drop inside the detector tube with respect to different sections of the detector tube in experiment to that of the predicted by Thome Et al. correlation and Friedel correlation for the given two experimental conditions -10°C.

In accordance with the above discussion, in the present work, those anomalous test results are excluded and the total valid tests are reduced to ten from a total of twenty one. The percentage deviation of total temperature drop over the detector tube for both the prediction methods [7, 44] with respect to the experiment is shown in [table 6]. The change in flow pattern and the vapor quality for the valid tests is shown in [table 7]. The Cheng-Ribatski-Quiben-Thome correlation (2008) [44] predicts 80 % of the valid test results within a deviation of 30 % where as Friedel correlation (1979) [7] predicts 50% of the valid test results within a deviation of 30%. Both the theoretical predictions [7, 44] are compared with that of the experiments in [fig 13, fig 14] for the valid tests. The Cheng-Ribatski-Quiben-Thome correlation (2008) [44] gives better prediction for low heat flux and low mass velocities tests as compared to the Friedel correlation (1979) [7].
Inlet Temperature [°C] | Power [watts] | Mass Flow [g/s] | Experimental | Thome Et al. prediction | Friedel prediction | Percentage deviation of theoretical predictions from experimental (ε)
---|---|---|---|---|---|---
-20 | 79.8 | 0.5 | 1.88, 1.12 | 2.93, 1.71 | 4.11, 2.38 | 55.66, 118.1
-20 | 111.5 | 1 | 4.92, 2.83 | 4.01, 2.41 | 7.9, 4.42 | 29.61, 34.46
-20 | 150 | 1.5 | 5.87, 3.37 | 4.14, 2.41 | 7.9, 4.42 | 29.61, 34.46
-20 | 150 | 1 | 5.55, 3.15 | 5.11, 2.89 | 6.49, 3.64 | 8.02, 16.91
-20 | 150 | 1.5 | 8.47, 4.66 | 5.14, 2.93 | 8.7, 4.78 | 39.3, 2.78
-20 | 222.5 | 1.5 | 11.42, 6.17 | 8.03, 4.5 | 10.62, 5.79 | 29.66, 7.01
-10 | 111.5 | 1 | 2.54, 1.86 | 2.69, 1.95 | 4.19, 3.02 | 5.97, 64.9
-10 | 111.5 | 1.5 | 3.52, 2.56 | 3.05, 2.21 | 5.38, 3.82 | 13.42, 52.56
-10 | 151 | 1 | 3.18, 2.32 | 3.59, 2.6 | 4.62, 3.31 | 12.85, 45.09
-10 | 226.4 | 2 | 8.31, 5.67 | 6.41, 4.45 | 9.24, 6.24 | 22.88, 11.19

Table 6 Percentage deviation (ε) of theoretical predictions from experimental results for the valid tests.

$$\varepsilon = \frac{|\text{experimental} - \text{theoretical}|}{\text{experimental}}$$

<table>
<thead>
<tr>
<th>Inlet Temperature [°C]</th>
<th>Power [watts]</th>
<th>Mass Flow [g/s]</th>
<th>Inlet Vapor Quality [%]</th>
<th>Final vapour Quality [%]</th>
<th>Change in flow pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>79.8</td>
<td>0.5</td>
<td>11.4</td>
<td>67.3</td>
<td>I-A</td>
</tr>
<tr>
<td>-20</td>
<td>111.5</td>
<td>1</td>
<td>3.4</td>
<td>42.7</td>
<td>I-A</td>
</tr>
<tr>
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<td>111.5</td>
<td>1.5</td>
<td>1.8</td>
<td>27.6</td>
<td>B-A</td>
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<tr>
<td>-20</td>
<td>150</td>
<td>1</td>
<td>2.4</td>
<td>53.9</td>
<td>I-A</td>
</tr>
<tr>
<td>-20</td>
<td>150</td>
<td>1.5</td>
<td>0</td>
<td>34.4</td>
<td>B-A</td>
</tr>
<tr>
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<td>B-A</td>
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<td>1.25</td>
<td>29.4</td>
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</tr>
<tr>
<td>-10</td>
<td>151</td>
<td>1</td>
<td>3.2</td>
<td>60.2</td>
<td>I-A</td>
</tr>
<tr>
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<td>226.4</td>
<td>2</td>
<td>0</td>
<td>41.5</td>
<td>B-A</td>
</tr>
</tbody>
</table>

Table 7 Vapor quality at inlet and outlet along with change in flow pattern for experiments performed at -10°C where I – Intermittent, A – Annular, B – Bubbly.
Figure 15.1 $T_s = -20^\circ C$ | $X_{in} = 11\%$ | $P = 80W$ $q = 3305W/m^2$ | $\dot{m} = 0.5g/s$ $M = 325$ kg/m$^2$s

Figure 15.2 $T_s = -20^\circ C$ | $X_{in} = 3\%$ | $P = 111W$ $q = 4586W/m^2$ | $\dot{m} = 1g/s$ $M = 650$ kg/m$^2$s

Figure 15.3 $T_s = -20^\circ C$ | $X_{in} = 2\%$ | $P = 111W$ $q = 4586W/m^2$ | $\dot{m} = 1.5$ g/s $M = 974$ kg/m$^2$s
CO2 based two phase cooling test set up for CMS trackers

Bibhudutta Mishra
National Institute of Technology Durgapur, India

Figure 15.4 $T_s=-20^\circ C$ | $X_{in}=2\%$ | $P=150W$ $q=6198W/m^2$ | $\dot{m}=1g/s$ $M=650kg/m^2s$

Figure 15.5 $T_s=-20^\circ C$ | $X_{in}=0\%$ | $P=150W$ $q=6198W/m^2$ | $\dot{m}=1.5g/s$ $M=974kg/m^2s$

Figure 15.6 $T_s=-20^\circ C$ | $X_{in}=0\%$ | $P=222W$ $q=9173W/m^2$ | $\dot{m}=1.5g/s$ $M=974kg/m^2s$

Figure 13 Comparison of the temperature of the micro channel with respect to different sections on the detector tubes in experiment to that predicted by Thome Et al. correlation and Friedel correlation for the given test conditions at -20°C.
CO\textsubscript{2} based two phase cooling test set up for CMS trackers

Bibhudutta Mishra
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Figure 16.1 $T_s=-10^\circ C$ | $X_{in}=2\%$ | $P=111 W$ $q=4586 \text{ W/m}^2$ | $\dot{m}=1g/s$ $M=650 \text{ kg/m}^2s$

Figure 16.2 $T_s=-10^\circ C$ | $X_{in}=1\%$ | $P=111 W$ $q=4586 \text{ W/m}^2$ | $\dot{m}=1.5g/s$ $M=974 \text{ kg/m}^2s$

Figure 16.3 $T_s=-10^\circ C$ | $X_{in}=3\%$ | $P=150 W$ $q=6198 \text{ W/m}^2$ | $\dot{m}=1g/s$ $M=650 \text{ kg/m}^2s$
Figure 16.4 $T_s = -10 \, ^\circ C \mid X_{in} = 0\% \mid P = 226W \quad q = 9338W/m^2 \mid \dot{m} = 2g/s \quad M = 1299kg/m^2$ s

Figure 16 Comparison of the temperature of the micro channel with respect to different sections on the detector tubes in experiment to that predicted by Thome Et al. correlation and Friedel correlation for the given test conditions at -10°C.

As a result the temperature over each section of the detector tube obtained from all the valid tests is compared with that of the predicted by Cheng-Ribatski-Quiben-Thome correlation (2008) [44] and Friedel correlation (1979) [7] in [fig 17].

Figure 17 Comparison of the temperature of the micro channel in experiment to that predicted by Thome Et al. correlation and Friedel correlation for the set of 10 valid tests.
Conclusion

The following conclusion are drawn from this project work.

1) CO₂ is radiation hard and has excellent thermodynamic properties for cooling in micro channels. The layer 1 of the pixel detector dissipates 144 W over a cooling pipe length of 5.5m, diameter of 1.4 mm and thickness 50 microns. So the detector tube used in the test is a micro channel. The saturation temperature is -20°C, -10°C, the mass velocities vary from 325 kg/m²s (0.5 g/s) to 1299 kg/m²s (2 g/s), the heat fluxes vary from 1.595 kW/m² (39 W) to 9.338 kW/m² (226 W) in the tests.

2) Cheng-Ribatski-Quiben-Thomé correlation (2008) [44], being the most updated flow pattern map based method, was chosen for predicting the pressure drop over the detector tube. Friedel correlation (1979) [7] is an extensively tested separated flow model which is also chosen for the purpose of comparison.

3) The flow pattern map predicts intermittent to annular flow transition for most of the tests and bubbly to annular transition for some of the low vapor quality and high mass velocities test. The analysis of the pressure drop data from the tests was useful in discarding some of the test results and hence the database was reduced to ten valid tests. Cheng-Ribatski-Quiben-Thomé correlation (2008) [44] predicts 80 % and the Friedel correlation (1979) [7] predicts 50 % of the valid test results within a deviation of 30 % for pressure drop over the detector tube.

4) Based on the literature review, Grönerrud (1972) [5] and Müllner-Steinghagen-Heck (1986) [8] correlation are the other best models for comparison. The anomalous tests can be conducted once again in the dry air based test set up for the sake of completeness.
Experience

The technical sessions with Hans and Joao have helped me in my reasoning abilities and sharpened my approach on how to tackle a problem. I have acquired new skills in handling software like MATHCAD, REFPROP-NIST and the hardware realization interfaced with LABVIEW. Interestingly it was an accident caused by overheating, as a result of which, I was able to take part in the reassembly of the set-up, and this allowed me to get a clear idea of the instrumentation of the set up. The CERN experience has broadened my overall outlook and further strengthens my motivation for pursuing a career based on research.

Acknowledgement

I would like to thank Hans Postema, my supervisor for his constant motivation and help throughout the project. I am grateful to Joao Noite for the experiments. I am thankful to Archana Sharma for all the memorable days here at CERN. Lastly, I would like to specially mention my institute NIT Durgapur, India for all the support and assistance.
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2) Slides and documents shared by Hans Postema.


