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EVAPORATIVE CO_2 HEAT TRANSFER MEASUREMENTS FOR COOLING SYSTEMS OF PARTICLE PHYSICS DETECTORS

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ABSTRACT

A major challenge in particle physics detectors is to transport the heat developed in their electronics to the outside world. Particle detectors require a minimum of material in order not to disturb accurate measurements of particle trajectories. CO_2 has superior behavior in small diameter - low material – tubes, although detailed experimental data are lacking. Understanding the behavior of evaporative CO_2 cooling in small diameter tubing is therefore of large interest for future detector cooling developments.

At the Dutch Institute for Subatomic Physics, Nikhef, we are developing an automated CO_2 test set-up able to scan the full phase space of mass fluxes, heat fluxes, vapor quality and temperature. A wide range of tube diameters (0.5 to 4mm) will be explored and data will be compared to the available models.

In this paper we will present the test setup and the first measurements of heat transfer, pressure drop, and dry-out behavior at room temperature. Lower evaporation temperatures down to -50°C will be explored in a later stage after an upgrade of the research plant.

INTRODUCTION

The Large Hadron Collider (LHC)[1] at CERN (Geneva) has become operational in the fall of 2009. The LHC is a particle accelerator that will collide protons at an energy and intensity that is an order of magnitude higher than ever reached before. With the LHC we may discover much about the behavior of matter at the smallest distances and we may shed a light on how the Universe behaved in its first few seconds. Essential to all potential discoveries are the big detectors that are built around the collision points of the protons. These are the microscopes that look into the collisions in detail.

For our research on cooling we focus on the detectors that are closest to the collision point of the proton beams. These detectors, the so-called trackers, have the task to measure accurately – within 10's of micrometers - the positions of the thousands of electrically charged particles that are produced when two protons collide head-on. Nowadays trackers are mostly made of solid state – i.e. silicon – detectors. These detectors usually consist of active sensor material in combination with readout electronics that are both generating heat. To transport this heat out of the detector a sophisticated cooling system is needed. In addition to the "normal" design considerations for a cooling system, we are subject to the following additional constraints:

- **Minimize material.** The cooling system is inside the volume where particles are traced, very close to the particle accelerator beam line. Any material here will deteriorate the precision of the measurements. Fortunately CO_2 allows for relatively small tube diameters compared to low-pressure evaporation coolers. First of all the viscosity of CO_2 is low. Second, CO_2 has a low dT/dP ratio which means that relatively large pressure drops are allowed without serious temperature gradients due to the change in evaporation pressure.
- **Tolerant to radiation.** The cooling system – at least the part inside the tracking volume – is exposed to intense radiation. All materials used in the system must therefore be radiation tolerant. This is required for both the system itself and the coolant. On the one hand the 2PACL cooling technique [2],[3] allows for placement of only passive i.e. un-breakable components in the LHC radiation zones. CO_2 can withstand large doses of ionizing radiation.
- **Low temperature.** Besides just removing the heat produced in the readout electronics, the cooling system must keep the solid state silicon sensors at a temperature well below 0°C. This significantly increases the lifetime of a silicon detector inside a high radiation environment. Evaporative CO_2 cooling theoretically allows temperatures down to -55°C. A typical detector needs a cooling temperature between -25 °C and -40°C.
- **Temperature stability.** We need to keep temperature fluctuations as small as possible in order to maintain the mechanical stability needed for precise position measurements. Temperature stability is guaranteed by the 2PACL technique that will be briefly discussed in the next section.

Currently the LHCb experiment [4] at the LHC already uses evaporative CO_2 cooling. The system is working well and other experiments in particle physics expressed interest to use CO_2 as well for future upgrades of the equipment. To support the design of new evaporative cooling systems we are assembling a test facility at Nikhef where we can thermally characterize detector structures and components. We will use the facility also to further investigate the behavior of CO_2 with emphasis on flow properties in small diameter tubes. The results of these measurements can then be used as input parameters for detector design. In this paper we present the first measurements of room temperature heat transfer of two stainless steel tube samples.

EXPERIMENTAL SETUP

We use evaporative CO_2 cooling at ambient temperature following the 2PACL technique (2-Phase Accumulator Controlled Loop) developed at Nikhef [2],[3] A schematic diagram of the cooling facility is shown in *Figure 1* and a picture of the setup is shown in *Figure 3*.

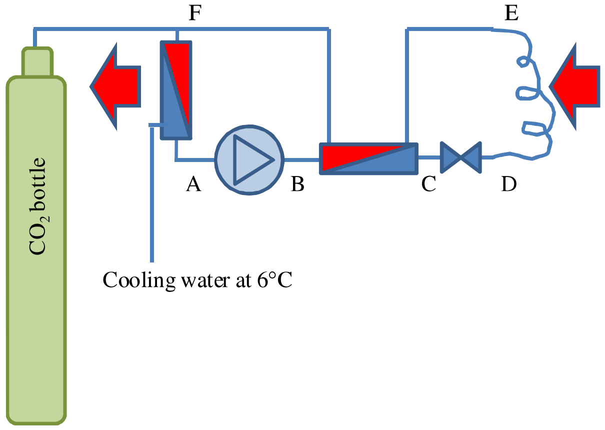

Figure 1: *Schematic view of the ambient temperature evaporative CO_2 cooling apparatus.*

A Gather 1M-J/12-11/X-SS/S/Qk200/DLC gear pump (A-B) circulates CO_2 liquid through the system. After the pump the CO_2 temperature is raised to the returning vapor temperature by means of a concentric tube heat exchanger (B-C). The experimental setup (D-E) is after a restriction/capillary (C-D). The returning vapor-liquid mixture is condensed and sub-cooled (F-A) by cooling water of 6°C in a concentric tube heat exchanger. The sub-cooled liquid is fed back to the pump.

The evaporator pressure is determined by an accumulator. It passively regulates the pressure inside the CO_2 return-line and thus in the experimental setup. The presented measurements are all done with a normal storage bottle as accumulator. The ambient temperature bottle controls the evaporator temperature in the experiment to be at the ambient temperature. *Figure 2* shows an example of what the 2PACL cooling loop for the ambient temperature cooling plant looks like in the enthalpy pressure diagram.

All measurements presented in this paper have been done with this ambient temperature cooling system. The cooling system is controlled by means of a Siemens S300 PLC: in this ambient cooler the only parameter that can be controlled is the CO_2 flow, which can be set by means of a profibus connection to the pump. In addition to the control, the PLC records the pressure, temperature, and the mass flow in the cooling plant.

The functionality of the PLC control will be increased, when the ambient temperature cooling apparatus is upgraded to a more versatile system that can span the full range of evaporative temperatures from -50°C to +27°C. The bottle will be replaced by an accumulator as it was used in LHCb and the concentric tube condenser by a plate heat exchanger. Both accumulator and condenser will be cooled by an external cryostat. The internal heat exchanger will be replaced by an electric heater to control better the inlet condition of the experiment.

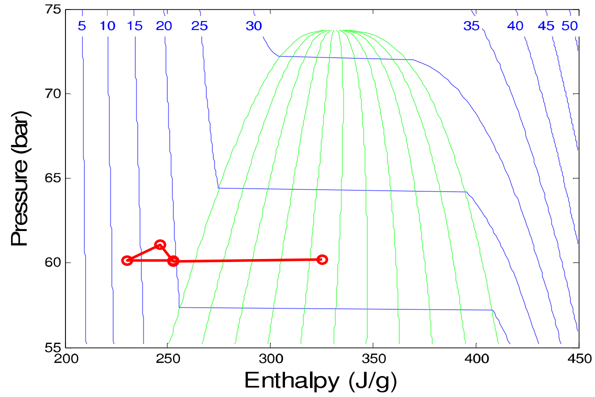

Figure 2: *Example of the 2PACL cooling cycle of the ambient cooling plant in the enthalpy pressure diagram. Since a pumped system is used, the cooling plant cycle is in the liquid phase, the experiment in 2-phase.*

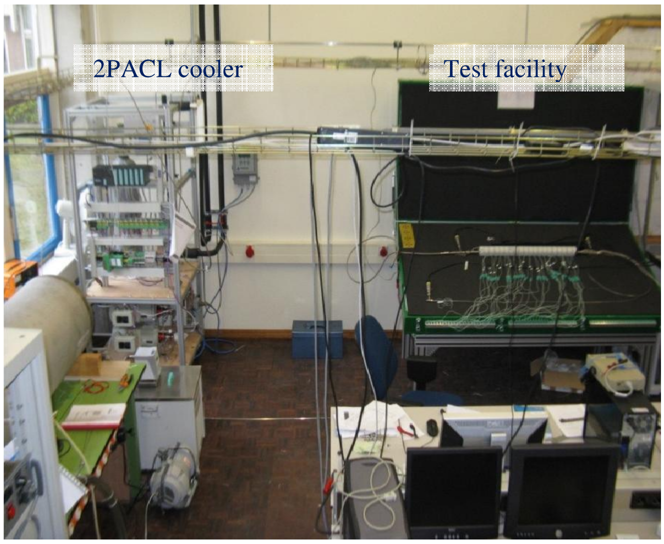

Figure 3: *Picture showing the ambient temperature CO_2 cooling apparatus (left) and the isolated test-facility (right). In the foreground the data-acquisition PC with PVSS software is visible that controls the experiment and gives the necessary input parameters to the cooling machine.*

The discussed experiments in this paper (D-E in *Figure 1*) were done on an ID=1.2mm and ID=1.6mm stainless steel tube with a length of 800mm. The tubes were heated running a DC current through the stainless steel tube over a length of 715mm using a remotely controlled Delta power supply. On the heated part of the tubes 20 equally spaced type-K thermocouples were attached. To avoid grounding loops a thin layer of kapton tape was folded around the tube in order to electrically isolate the thermocouples from the sample. The main thermal effect of the kapton tape is a longer response time of the thermocouples: we estimated that the offset in temperature is below the measurement sensitivity. Readout of all thermocouples was done with a DT800 datalogger (http://www.datataker.com). In addition two thermocouples and pressure sensors are located on both the in- and outlet of the tube next to the heated zone. A picture of the experimental test facility is shown in *Figure 3*.

The readout of the lab-experiments and the control of the cooling plant have been integrated with a PC through PVSS Scada software: PVSS Scada software is widely used in particle physics to control for example the LHC and its detectors. The readout and control of the PLC and DT800 datalogger are done through ordinary Ethernet connection, while control of the power supply and readout of additional pressure sensors is done through a CANBUS interface. Due to the high level of readout-integration it has become possible to do a fully automated characterization of the thermal behavior of a sample. In the current system it usually takes in the order of a few hours to scan through the full range of mass flux and power density. After the cooling plant upgrade we will also be able to scan through the full temperature range. An additional advantage of the integrated approach is that it is easy to correlate cooling plant data with the data from the experimental setup, since these are contained in the same data set.

MEASUREMENT PRINCIPLE

The test set-up measures the in- and outlet temperatures and pressures. On the test tube thermocouples are mounted on the heated zone. The in and outlet sensors are mounted outside the heated zone. The coolant at the inlet of the test tube is kept single phase so the combination of pressure and temperature can be used to determine the inlet enthalpy. The enthalpy is derived from the Refprop database [5] which is implemented in Matlab. Matlab is used to analyze and plot all measurements. For each thermocouple location the pressure and enthalpy with respect to the known inlet condition is calculated. The temperature measurement is corrected for thermal conductivity from the outside of the tube wall to the inside.

ENTHALPY

The enthalpy of each sensor location is calculated from the known inlet enthalpy, the mass flux and the applied heat flux.

$$H(z) = H_{inlet} + \frac{4*z*\Phi}{ID*\dot{m}} \qquad \textbf{(1.1)}$$

Where H is the enthalpy, Φ the heat flux, z the position along the tube, ID the inner diameter of the tube and $\dot{m}$ the mass flux. The enthalpy calculation of equation 1.1 can be checked in case superheated vapor is present at the outlet. In this case the enthalpy can be derived as well from the Refprop database as a function of the measured temperature and pressure.

PRESSURE DROP

The pressure drop over both stainless steel tubes has been measured as a function of the mass flux (see *Figure 4*). The pressure drop was measured by subtracting the pressure measured by absolute pressure sensors at both the inlet and outlet of the tubes. A quadratic fit to the points, indicated by the dotted lines, describes the data well.

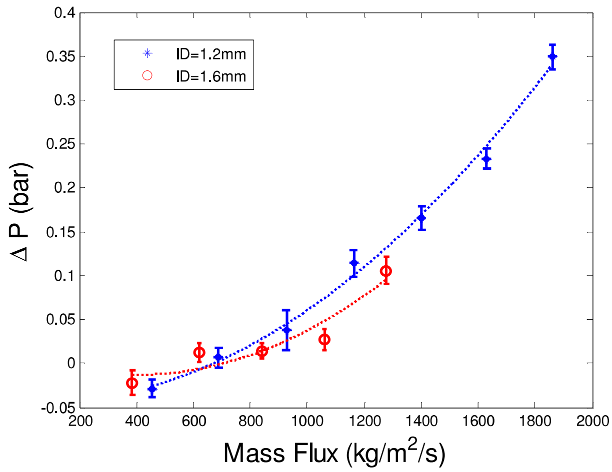

Figure 4: *Pressure drop over the ID=1.2mm and ID=1.6mm stainless steel tubes as a function of the mass flux. The dotted lines represent a quadratic fit to the points.*

To calculate the temperature of the CO_2 at every location on the tube we need to estimate the pressure along the tube. Since we do not know the exact profile of pressure as a function of position we assume a simplified linear dependence of pressure on position. In reality this is not the case as the vapor quality is not constant.

$$P(z) = P_{inlet} + (z/L)\Delta P \qquad (1.2)$$

Where z is the position along the tube, P_{inlet} the pressure at the inlet of the tube, ΔP the pressure drop and L the length of the tube. For the ID=1.2mm tube the pressure drop of 350mbar at the highest mass flux results in a change in evaporation temperature of 0.2°C. At low temperatures a correction for the pressure drop is crucial for good estimation of the CO_2 temperature.

It has to be noted though that there is a 20-30 mbar offset in the pressure measurement. To increase the precision of our saturation temperature calculation we need to use more accurate pressure sensors. We will also add a differential pressure sensor in the future to measure the pressure drop directly. The calculated pressure of equation 1.2 is used to calculate the CO_2 evaporation temperature at each temperature sensor location. At 20°C an error in the pressure measurement of 50mbar results in an offset of 0.05°C in the calculated evaporation temperature. This is well below the uncertainty of the thermocouples used to measure the stainless steel tube wall temperatures. At a temperature of -40°C the temperature effect is of the order of 0.1°C: a small value for which we need to correct in order to obtain accurate measurements of heat transfer.

TEMPERATURE PROFILES

The temperature along both stainless steel tubes have been measured at 20 equally spaced locations. *Figure 5* shows the temperature as a function of the heat flux for three of the sensors: one located at the beginning of the heated length (z=0.02m), one in the middle (z=0.24m) and one close to the end (z=0.65m). The heat flux range is chosen such that it covers the full range of cooling power we expect for new applications in particle physics detectors. The line with blue stars is close to the inlet and boiling starts at high heat fluxes (52 kW/m^2), the line with the green dots is near the outlet. Here the boiling starts already around 14 kW/m^2 and dry-out sets in at 62 kW/m^2.

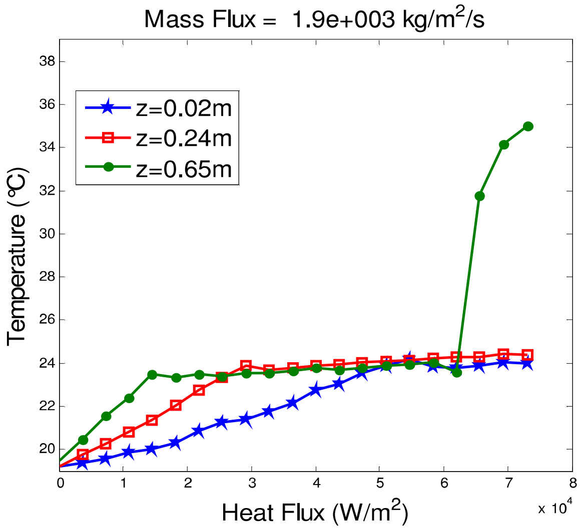

Figure 5: *Measured temperature as a function of the heat flux for the ID=1.2mm tube. The different lines show the temperatures at three different locations.*

Figure 6 shows the temperature along the ID=1.2mm tube as function of enthalpy for a mass flux of 1.9·10^{3}kg/m^2/s. The fluid temperature at each location is calculated from the enthalpy of equation 1.1 and the pressure of equation 1.2 using the Refprop database. This method of temperature calculation is independent of the local phase. It always derives the real CO_2 condition from Refprop which can be sub-cooled, saturated or superheated. The dashed lines show these calculated temperatures. The sub-cooled liquid to 2-phase transition is clearly visible by the sharp bend. In *Figure 7* an example of the 2-phase to super-heated vapour transition is shown.

At a relatively low heat flux of 3.28·10^{4}W/m^2 (red squares) the temperature on the tube wall decreases suddenly at the transition from sub-cooled to saturated liquid. For larger enthalpies the temperature slowly decreases as the liquid passes through the tube, due to the drop in pressure. The calculated saturation temperature profile (red dotted line) shows the same behaviour. At the higher heat flux, the transition from the sub–cooled liquid to 2-phase is not so clear. Clearly visible here is the sudden temperature increase around x=0.45. Dry-out has set in while the fluid temperature remains saturated (blue dotted line).

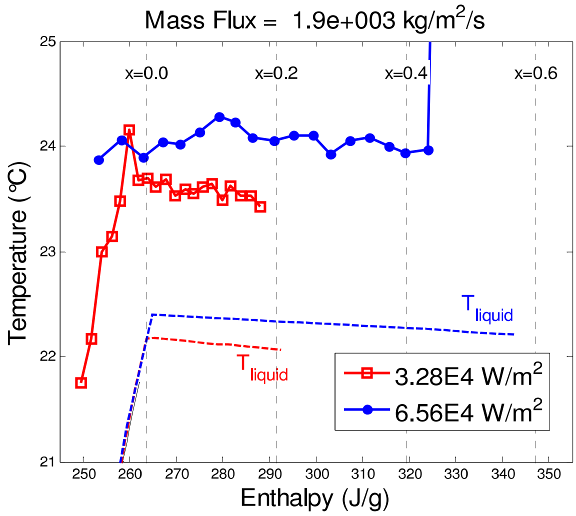

Figure 6: *Temperature along the ID=1.2mm cooling tube as a function of the CO_2 enthalpy for two values of the heat flux. The mass flux is 1.9·10^3 kg/m^2/s. The dotted lines show the calculated saturation temperature at the same enthalpy.*

Figure 7 shows the temperature as a function of enthalpy for a much lower mass flux of 4.5·10^2 kg/m^2/s. At x>0.75 dry-out becomes clearly visible. After fully evaporating the liquid, the temperature of the tube is determined through gas cooling, which shows inferior heat transfer compared to evaporative cooling (note the different vertical scales on *Figure 6* and *Figure 7*).

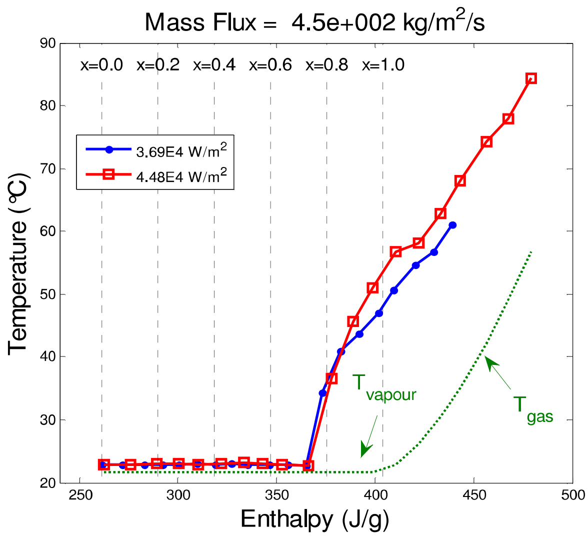

Figure 7: *Temperature along the ID=1.2mm cooling tube as a function of the CO_2 enthalpy for two values of the heat flux. The mass flux is 4.5·10^2 kg/m^2/s. The dotted line shows the estimated vapour/gas temperature at the same enthalpy.*

HEAT TRANSFER

In this section we present our first results on measurements of the heat transfer coefficient of CO_2 in small tubes at room temperature. The heat transfer coefficient is defined in the usual way as:

$$HTC = \frac{\Phi}{T_{in} - T_{fl}} \qquad (1.3)$$

where Φ is the heat flux from the tube into the liquid, T_{fl} the temperature of the fluid and T_{in} the temperature of the inner tube wall.

We measure the temperature, T_{out} , on the outer surface of the tube. The heat is developed equally in the tube wall. By solving the heat transport equation in cylindrical coordinates we obtain for T_{in} :

$$T_{in} = T_{out} + \frac{\dot{q} * r_{out}^2}{2 * \kappa} * \ln\left(\frac{r_{in}}{r_{out}}\right) + \frac{\dot{q}}{4 * \kappa} * (r_{out}^2 - r_{in}^2) \qquad (1.4)$$

Where $\dot{q}$ is the volumetric power density and κ the thermal conductivity of the tube. For this equation we assume that all the heat that is generated is absorbed through the inner surface of the tube by the CO_2 coolant. Since we are operating our cooling facility close to room temperature we expect the effects of heat leaks to be small. The temperature corrections we calculate in this way vary from 0-0.5°C depending on the power density. Although this correction is rather small it still constitutes a 15-20% effect on the HTC: especially for large HTC values when the temperature differences are small. In the future when we run cold measurements the heat leak will be evaluated by measuring the temperature increase at a sub cooled liquid flow.

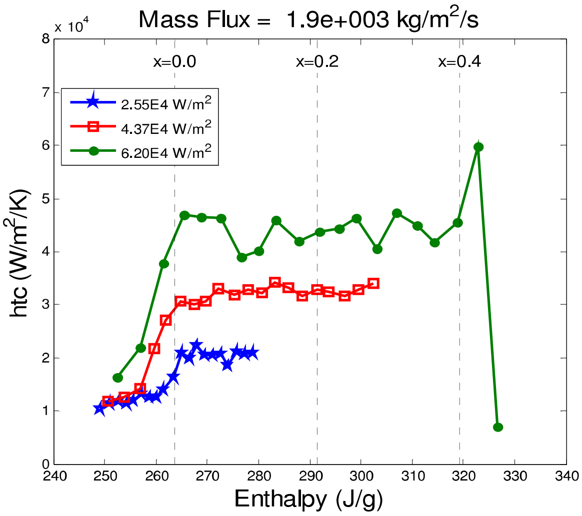

Figure 8: *Heat transfer coefficient as a function of enthalpy and heat flux for the 1.2mmID tube*

Figure 8 shows an example of the heat transfer coefficient calculated with the temperature correction of equation 1.4 as a function of the enthalpy. The HTC increases from liquid to 2-phase heat transfer and remains constant at increasing vapor qualities. The heat transfer coefficient increases with the applied heat flux.

The value for the evaporative HTC ranges from about $2{\cdot}10^4$ W/m^2/K at low heat fluxes of the order of $5{\cdot}\ 10^4$ W/m^2/K at high heat fluxes. We expect lower HTC's once we will measure the same samples in the lower temperature range (down to -40°C) which is the interesting range for particle physics applications. Around x=0.45 a dry-out is observed by a sudden decrease of the heat transfer coefficient. Just before this dry-out an increase of the HTC is observed, which we do not completely understand at the time of writing this paper.

In Figure 9 the heat transfer results of 62kW/m^2 from figure 8 are plotted in a flow pattern/heat transfer plotting tool from the online engineering databook III of Thome [6]. The heat transfer prediction according to Kandlikar [7] is added in the same figure. The measurements show a much more constant heat transfer over vapor quality and a sudden decrease at dry-out. Both models show a slow dry-out slope.

The upgrade of the cooling plant to colder temperatures will give us the possibility to scan the full phase space of mass flux, heat flux, temperature and tube diameter. The automatic measurement protocol will generate a database at which we will check the available models in the future.

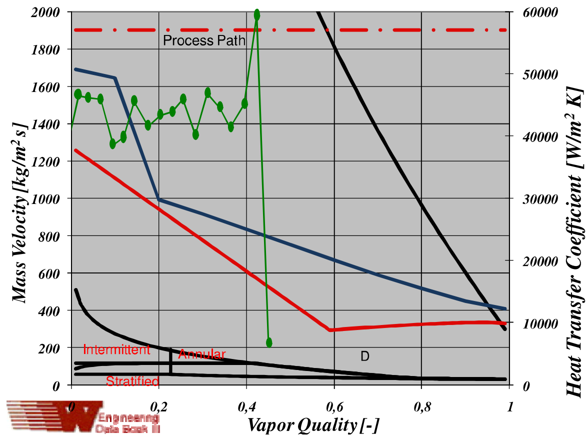

Figure 9: *The heat transfer measurement of 62 kW/m^2 from figure 8 plotted in the Thome flow pattern map. The red curve is the heat transfer calculated by the Thome, the blue curve is the heat transfer according to Kandlikar.*

DRY-OUT BEHAVIOR

To further investigate the dry-out behaviour in the samples of stainless steel tubes, we have plotted the HTC divided by the heat flux as a function of the CO_2 vapour quality (see Figure 10 and Figure 11). In these figures all the measured HTC from all sensors at all settings of heat flux and CO_2 mass flux are plotted. Both samples show a high HTC compatible with CO_2 evaporative cooling up to a critical value, x_c , of the vapour quality. Above x_c the relative HTC drops to a much lower value: still some heat is rejected, but now by means of gas cooling. The ID=1.2mm tube dries out for vapour qualities in the range of x_c=0.45 to 0.65, while the larger ID=1.6mm tube has a significantly higher dry out range between x_c=0.85 and 0.95.

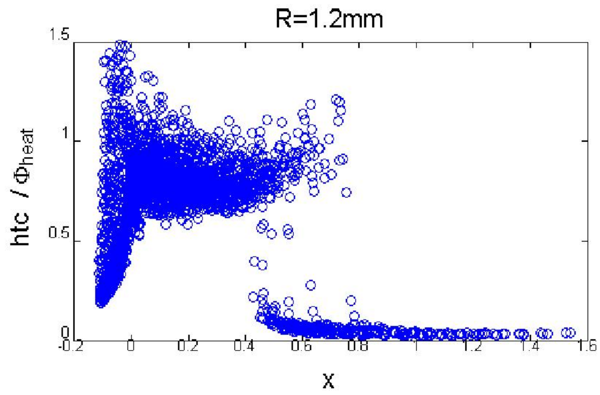

Figure 10: *Heat transfer coefficient divided by heat-flux as a function of the CO_2 vapour quality for an ID=1.2mm stainless steel tube. Note that the wider range of HTC/Φ_{heat} is at x<0, which is sub-cooled.*

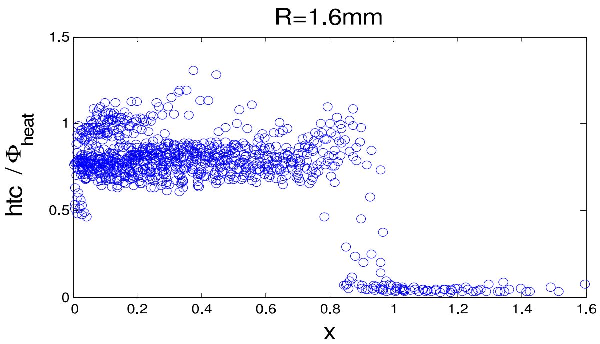

Figure 11: *Heat transfer coefficient divided by heat-flux as a function of the CO_2 vapour quality for an ID=1.6mm stainless steel tube.*

CONCLUSION AND OUTLOOK

We have demonstrated a working CO_2 cooling plant at room temperature working according to the 2PACL principle. The plant facilitates precise measurements on CO_2 properties in small diameter tubes. The automatic measurement method is able to scan relatively easy an experimental tube, the data taken is very clean and easy to process.

The first results of heat transfer coefficients have been obtained on a 1.2mm ID and 1.6mm ID stainless steel tube. The heat transfer coefficients we measure are roughly in agreement with the model predictions by Thome et al., though we see a sharp increase in heat transfer coefficients just before dry-out sets in. At the time of writing this paper this phenomenon is under study. Furthermore we have observed that dry-out sets in at higher vapor quality for a larger inner-diameter tube.

The aim of our measurement program is to map all parameters relevant to heat transfer for CO_2. In the presented tests a 2d scan was made (heatflux & massflux), in the future a 3d scan can be performed including pressure and hence temperature. This way a full data base of heat transfer and pressure drop data will be generated, which we will compare to the available theory. The test set-up will also be used to characterize the thermal behavior of particle physics detector structures which will use CO_2 cooling for their thermal control.

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