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FACULTY OF ENGINEERING AND DESIGN

FINAL YEAR BEng PROJECT REPORT (ME30227)

Experimental Assessment of an Optimass 6400 Mass Flow Meter for Determining CO_2 Vapour Quality

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05/05/2015

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Assessor: *Dr. Martin Ansell*

Experimental Assessment of a Krohne Optimass 6400 Mass Flow Meter for Determining CO_2 Vapour Quality

Final Year Project Report

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May 2, 2015

Abstract

Acknowledgments

Thanks to Dr. Roger Ngwompo, my academic supervisor, and Dr. Martin Ansell, FYP coordinator, for making my continued collaboration with CERN possible. I'd also like to thank Nicola Spadavecchia, Bart Verlaat and Jerome Noel for their technical support. Finally, my thanks to Paola Tropea, my industrial supervisor, for her sharp questions and crucial guidance throughout my research.

Terms and Acronyms

CERN The European Oranization for Nuclear Research

Nikhef National Institute for Subatomic Physics, Amserdam, Netherlands

HEP High-Energy Physics

CMS Compact Muon Solenoid - a CERN experiment

LHC Large Hadron Collider

2PACL Two-phase accumulator control loop A planned shutdown of the LHC between February 2013 and April 2015 for maintenance and upgrade.

CFCs Chlorofluorocarbons

TIF Tracker Integration Facility

PH-DT CERN Physics Department, Detector Technologies Group

EGM Entrained Gas Management

DAQ Data Acquisition

SCADA sc

PWM Pulse Width Modulation

R744 Refrigerant Code for CO_2

Sub-cooling sub

Interaction Point point

.csv Comma-Seperated Value

C_6F_{14} Perflourohexane, a common industrial refrigerant and electrical insulator.

Symbols

Symbol	Property	Default Unit
H	Enthalpy	J
X	Vapour Quality	%
T	Temperature	°C
$\dot{m}$	Mass Flow Rate	kgs^{-1}
P	Pressure	bar abs
$\dot{Q}$	Heat Load	Watts
ϕ	Void Fraction	%
G	Mass Flux	$\text{kgs}^{-1}\text{m}^{-2}$
I	Current	Amperes
V	Voltage	Volts
p	Power	Watts
ρ	Density	kgm^{-3}
v	velocity	ms^{-1}

Contents

1. Introduction

CERN's PH-DT group is undertaking extensive research and development in the area of evaporative CO_2 cooling for particle detectors. A crucial parameter in the design and commissioning of these systems is vapour quality - the mass fraction of fluid that is vapour. Krohne, a supplier of instrumentation for the process industry, has approached CERN with a new instrument with potential to indirectly determine vapour quality through a measurement of 2-phase density. This study seeks to evaluate this promising new technlogy that would be directly relevant to the coming decade of R&D.

1.1 CO_2 Cooling at CERN

The particle detectors at CERN's various experiments require cooling to manage the heat load of the detector electronics, radiation from the interaction point and heat leak from the ambient environment. Evaporative CO_2 cooling has become the predominant candidate technology for future particle trackers in HEP. CO_2's combination of thermodynamic properties and radiation hardness make it ideal for HEP applications - it can be used in highly radioactive areas and is considered environmentally friendly. In addition, it cools efficiently in small-diameter tubes, minimising the material budget - a crucial metric representing the amount of non-instrumentation material inside the particle detector.

The C_6F_14 current cooling system for the pixel detector, the innermost layer of the CMS tracker, is being replaced with a CO_2 system aned a transition to this technology is foreseen for the entire CMS tracker by the end of 2024.

1.2 2-Phase Accumulator Controlled Loop

The CO_2 systems at CERN implement the 2PACL design. [?]. This involves pumping liquid coolant into the the detector, where it is expanded and cools its surroundings by partially evaporating. After cooling the detector with the latent heat of vaporisation, the mix of liquid and vapour returns to the plant by way of a condenser, which returns it to pure liquid phase for pumping. An accumulator filled with 2-phase fluid sits on

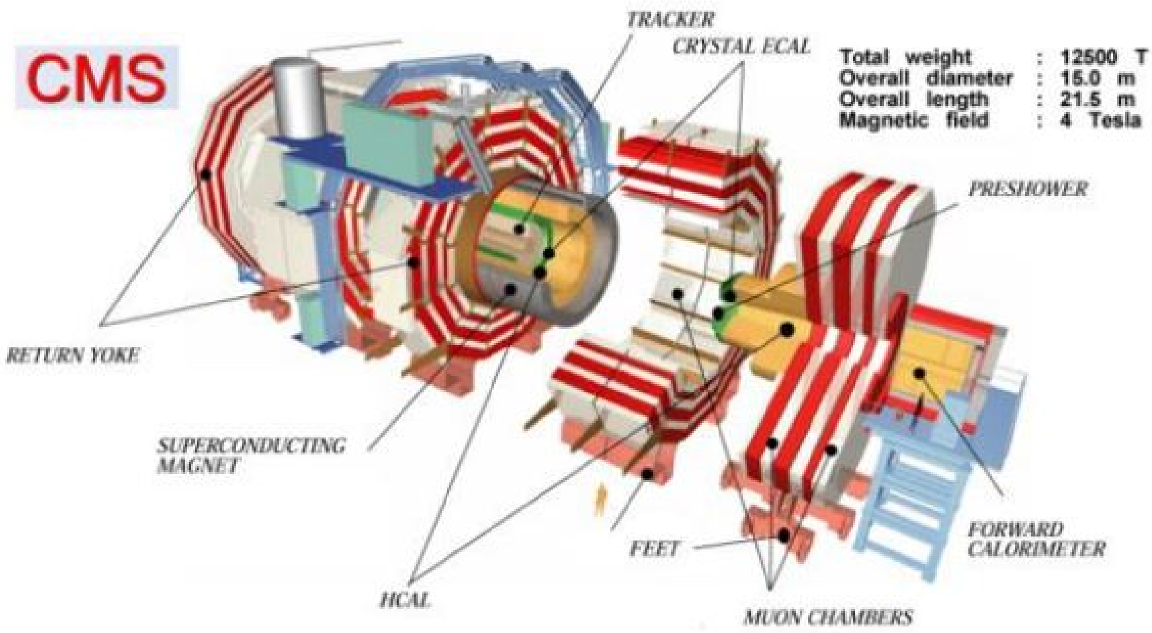


Figure 1.1: A diagram of the CMS particle detector on the LHC. [12]

the return line of the circuit, its pressure determining the position of the coolant temperature (and pressure as both are saturated), and therefore the position of the cooling cycle on the P-h diagram. Accumulator pressure is regulated using an array of heaters and a heat exchanger with an independent chiller circuit that also cools the condenser. The cycle and a schematic of the 2PACL concept are shown in figure 1.2.

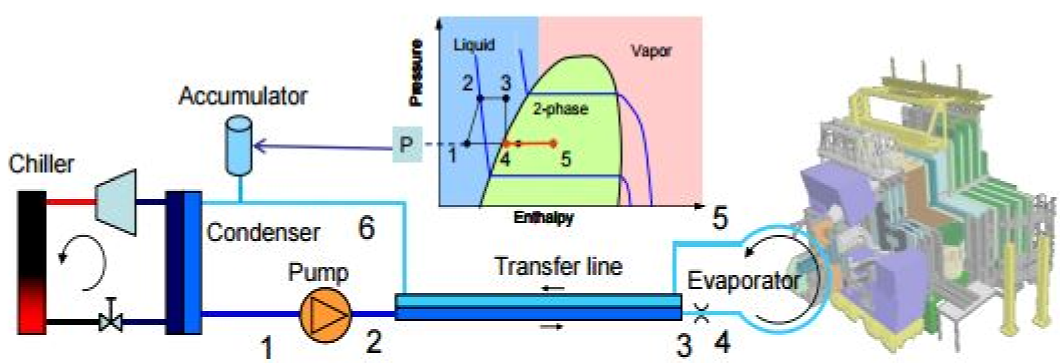


Figure 1.2: A schematic of the 2PACL concept as implemented in Thermal Control System of the LHCb Velo project at CERN [13]

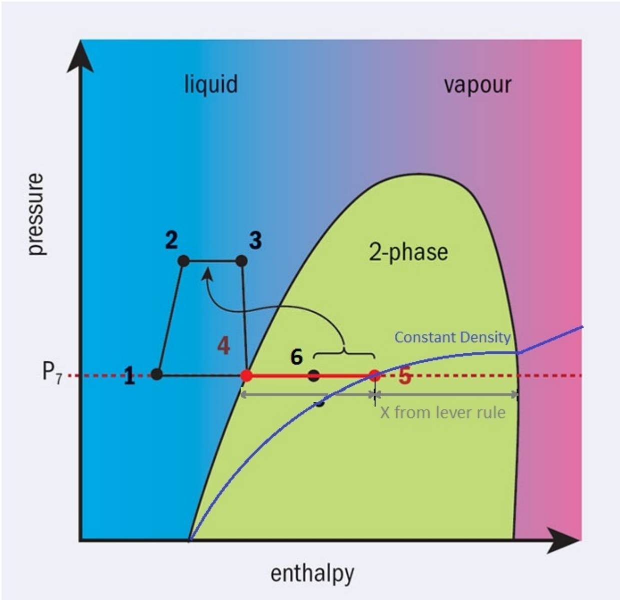


Figure 1.3: Principle for determining vapour quality, X, from two-phase density. Adapted from B. Verlaat. [18]

1.3 Vapour Quality and 2-Phase Density

Vapour quality refers to the fraction of a fluid's mass that is in the vapour phase.

$$X = \frac{m_{vapour}}{m_{fluid}} \tag{1.1}$$

In 2PACL cooling systems, the vapour quality after the coolant evaporates in the detector volume is an essential system parameter indicating the amount of evaporation that has occurred. The quality determines how far from the coolant is from dry-out, where a dramatic decrease in heat transfer coefficients may occur, causing a sudden decrease in cooling. A real-time calculation of vapour quality would allow the design of leaner cooling systems as dry out conditions can be observed before they occur, reducing the safety factors taken in sizing the liquid mass of the system.

Vapour quality at any point on a P-h diagram can be determined using the lever rule inside the vapour dome. In 2PACL, the challenge is mapping the fluid's exact location. In pure liquid, any point on the P-h diagram can be determined from pressure and temperature, but in phase transition these values are saturation conditions, and therefore a third variable is needed. One obvious choice is density, as shown in Figure 1.3. By knowing the local pressure and density, the exact point in the vapour dome, and therefore the vapour quality, can be determined.

Figure 1.4: The Krohne Optimass 6400 mass flow meter.

1.4 The Krohne Optimass 6400

The Optimass 6400 is a new twin bent tube coriolis mass flow meter. It features 3 independent measurements, from which it calculates 7 output signals. The 3 fundamental measurements to be assessed are:

- Mass Flow Rate - Coriolis principle.
- Density - Natural frequency of an oscillating tube.
- Temperature - Internal probe.

The instrument is unique because of its Entrained Gas Management - it is able to continue reading mass flow, density and temperature of 2-phase flow. The instrument's accuracy has been measured using liquid water and air bubbles, but never with a single fluid in 2 phases.

1.5 Aims, Objectives and Documentation

This study is an initial evaluation of the Optimass 6400's steady-state measurement accuracy over a wide operating envelope. Its aim is to evaluate the validate the strategy for determining vapour quality, quantify the attainable measurement under various conditions, and identify performance trends and areas for further research. Specific goals are given below:

- Compare mass flow and density readings with reference instrumentation and theory over a range of temperatures and vapour qualities.

- Quantify the instrument's steady-state performance and, if possible, identify an effective performance envelope.
- Express the instrument's accuracy in terms of vapour quality.
- Investigate the physical phenomena behind any performance trends.
- Identify areas for further research.

This report documents the background to the problem and relevant literature, describes the method employed to test and analyse the sensor's performance in 3, and the results of the testing in 4. Further, it documents speculation as to the cause of performance trends revealed in 4 and identifies areas for further research in **??**.

2. Literature Review

2.1 Behaviour of 2-Phase CO_2

2.2 Determining Vapour Quality

Literature on direct measurement of vapour quality is scarce, especially for CO_2. B.R. Jean presented a steam quality sensor that employs microwaves, yielding an accuracy of 2.8%. [24]. The operating principle relied on the dielectric properties of water. A review of steam quality measurement approaches conducted by Dorman and Fridman [25] evaluated calorimeter, chemical tracer and flow seperation methods, revealing their significant drawbacks. The authors then presented a new theoretical method for measuring vapour fraction, but it was limited to fluid in a static container.

Void fraction, defined as the volumetric fraction of fluid in the vapour phase, is an intuitive candidate for an inderect measurement of vapour quality.

$$\phi = \frac{V_{vapour}}{V_{fluid}} \tag{2.1}$$

Indeed, several methods have been developed for the measurement of void fraction, relying on capacitance measurement [22], x-rays [21], electron sources [19] and gamma ray densiometers [20]. However, the conversion of void fraction to vapour quality is far from straightforward, as the mass fraction of vapour depends on the density of both the vapour and the fluid:

$$X = \phi \frac{\rho_{vapour}}{\rho_{fluid}} \tag{2.2}$$

Emperical relations have been developed, most notably by Zuber and Findaly, between void fraction and vapour quality, but their complexity and limited range makes them impractical for a real-time application.[23].

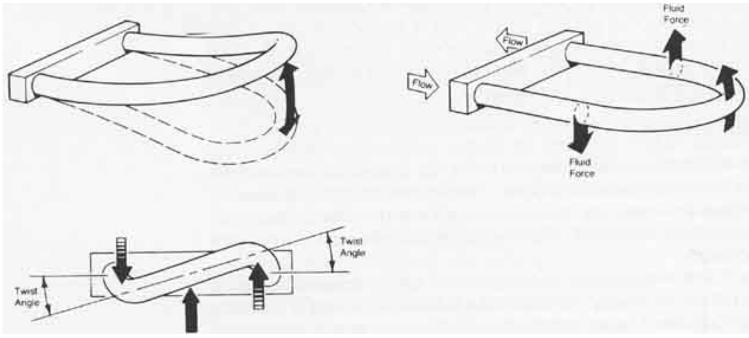


Figure 2.1: The working principle of coriolis flow meters. [**?**]

2.3 Measuring 2-Phase Density

2.4 Coriolis Flow Meters' Performance in 2-Phase

Coriolis flow meters induce a phase shift in the forced oscillations of two bent tubes using the Coriolis principle. As the tubes vibrate at their natural frequency, the velocity of the flow as it is directed radially toward and away from the axis of oscillation in the bent sections induces a phase shift varying linearly with the mass flow rate of the fluid through the instrument. [1] A schematic of the principle is given in figure 2.1.

Density, when independently measured in coriolis flow meters, is typically determined from the resonant frequency of the bent tubes. [1] The frequency is a function of the tube stiffness and mass. So any change in mass reflects a change in density of the fluid insisde the tube. The sensor corrects for temperature effects on stiffness and, with a known tube volume, determines the density.

Both of these measurement principles can be severely disrupted by 2-phase flow. Entrained gas may create slip planes between the phases, which cause unpredictable forces and vibrations.[**?**][17] This leads to two problems in instrumentation: first, the unexpected vibrations disturb sensitive electronics. Second, the slip between the phases dampens forced vibrations, possibly stopping the sensor from reading altogether. In a typical coriolis flow meter, the first symptom of entrained gas is the drive gain, the power required to force the tubes' oscillation, rising to 100%. [**?**][14]

Some manufacturers of process instrumentation have developed products to detect entrained gas. The Emerson Rosemount 3051S Pressure Transmitter, for example, employs statistical methods to detect characteristic frequencies of entrained gas.**??**

The Optimass 6400 is a physical copy of the older Otpimass 6000. But what makes it unique is the MFC400 electronics chip that it interfaces with. These electronics deliver Entrained Gas Management. A typical flow meter cannot handle 2-phase flow because the slip planes between the liquid and vapour phases damp the oscillations, causing the instrument to stop reading. Entrained Gas Management employs advanced signal processing and a completely digital drive signal to allow the instrument to continue measuring in 2-phase flow. [8][17]

3. Methods

3.1 Experimental Methods

Laboratory research was carried out using the future CMS pixel detector cooling system located in the Tracker Integration Facility clean room at CERN. This cooling system, hereafter referred to as *TIF*, employs the *2PACL* concept for evaporative CO_2 cooling. It allows active control of the coolant temperature, its flow rate and the heat load applied to it.

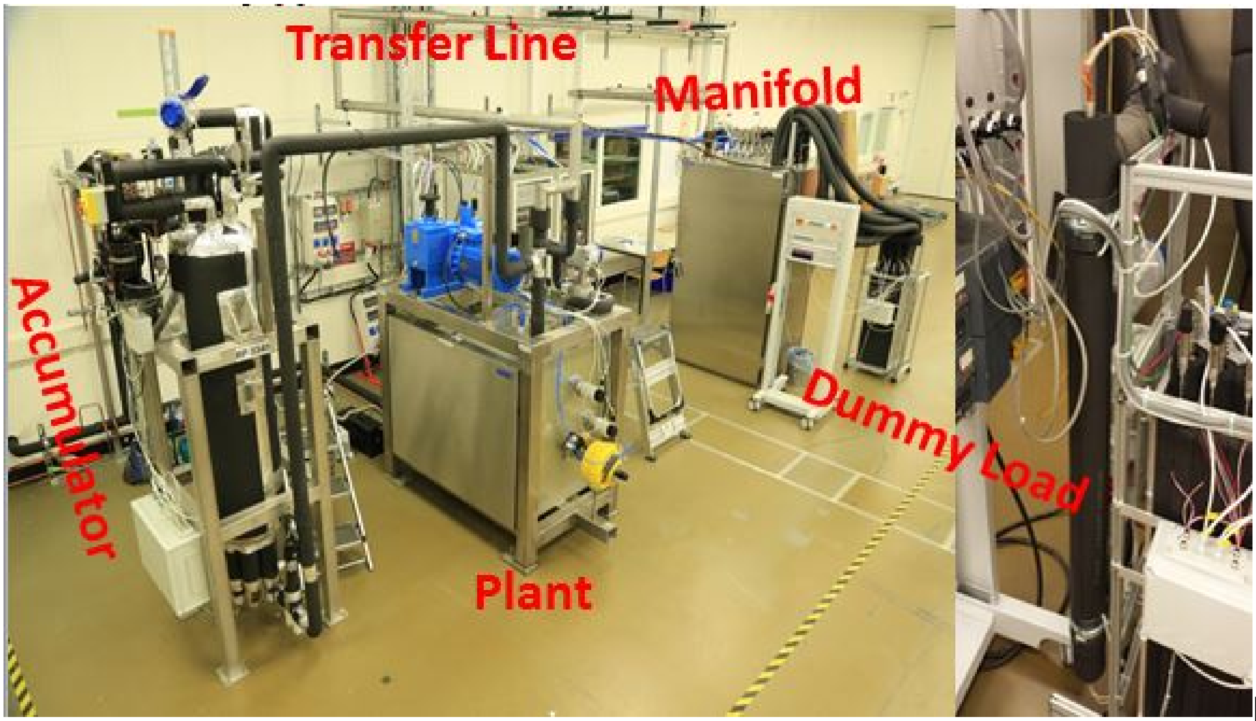
TIF consists of a membrane pump routing liquid CO_2 through a concentric transfer line to a manifold where the flow is split and can be heated. *Dummy Load* heaters represent the detector heat load, evaporating the CO_2 in the manifold. An accumulator containing 2-phase fluid on the return line of the manifold regulates the pressure set point using an array of heaters and a heat exchanger. A freon chiller cools the accumulator and the condenser at the pump inlet.

A full Process and Instrumenation Diagram is given in Appendix **??**.

3.1.1 Apparatus

The TIF cooling system services 8 cooling loops in the manifold and includes several bypasses, heaters and instrumentation that are mostly relevant to the start-up procedure and are configured using a series of pneumatic, manual and electro-mechanical valves. The plant was configured the same way for all tests: with all bypass loops closed, and a single loop, number 7424, open in the manifold. This configuration ensured all fluid leaving the plant passed through this loop and the Optimass instrument, and allows the experimental apparatus to be represented by a simplified P & I diagram given in figure **??**.

The Optimass instrument was mounted on a test stand close to the *TIF* manifold, as shown in figure 3.3a. Following guidance from Krohne, it was mounted upside-down, with the electronics module closer to the floor. The instrument's discharge was connected through a flexible pipe to the the return lines of loop 7424 in the *TIF* manifold. On the supply side, the instrument was connected directly to the discharge of the heating section. The heating section of loop 7424 consists of a 35 mm OD vertical pipe welded to



[h!]

Figure 3.1: The TIF cooling plant[L] and dummy load heater [R]. [15]

two tee unions. Two cartridge heater inside 22 mm pipes are axially inserted into the pipe through the tee fittings, as shown in figure 3.3b. A drawing of the heater is given in Appendix C. The flow enters the heating section radially with respect to the heaters through the lower tee union. It is forced into an anuular shape encircling the heater, and flows upward to the discharge tee-union. It then enters a short unobstructed circular series of fittings before reaching the Optimass instrument. Guidance from Krohne engineers and the instrument documentation indicated that the geometry at the sensor in let was satisfactory. The vacuum-insulated instrument, as well as all exposed piping, was covered with a 20 mm layer of *Armaflex* insulation to mitigate heat pick-up. All fittings were leak tested at 50 bar gas using a CO_2 sniffer prior to testing, and the instrument's position and inlet conditions respected the guidelines given in Appendix, as well as input from Krohne engineers.

3.1.2 Control and Data Acquisition

All of the instrumentation on the TIF plant, the dummy load and the Optimass flow meter is cabled to a central PLC in the TIF clean room. Each instrument communicates a 4-20 mA analogue current signal, which is mapped by the PLC to produce a value in the correct units. All of the data is continuously logged to a server, day and night. The data is logged using a change or duration algorithm - logging new data only when one of the signals has changed. This produces a sampling rate of several Hz during transient conditions

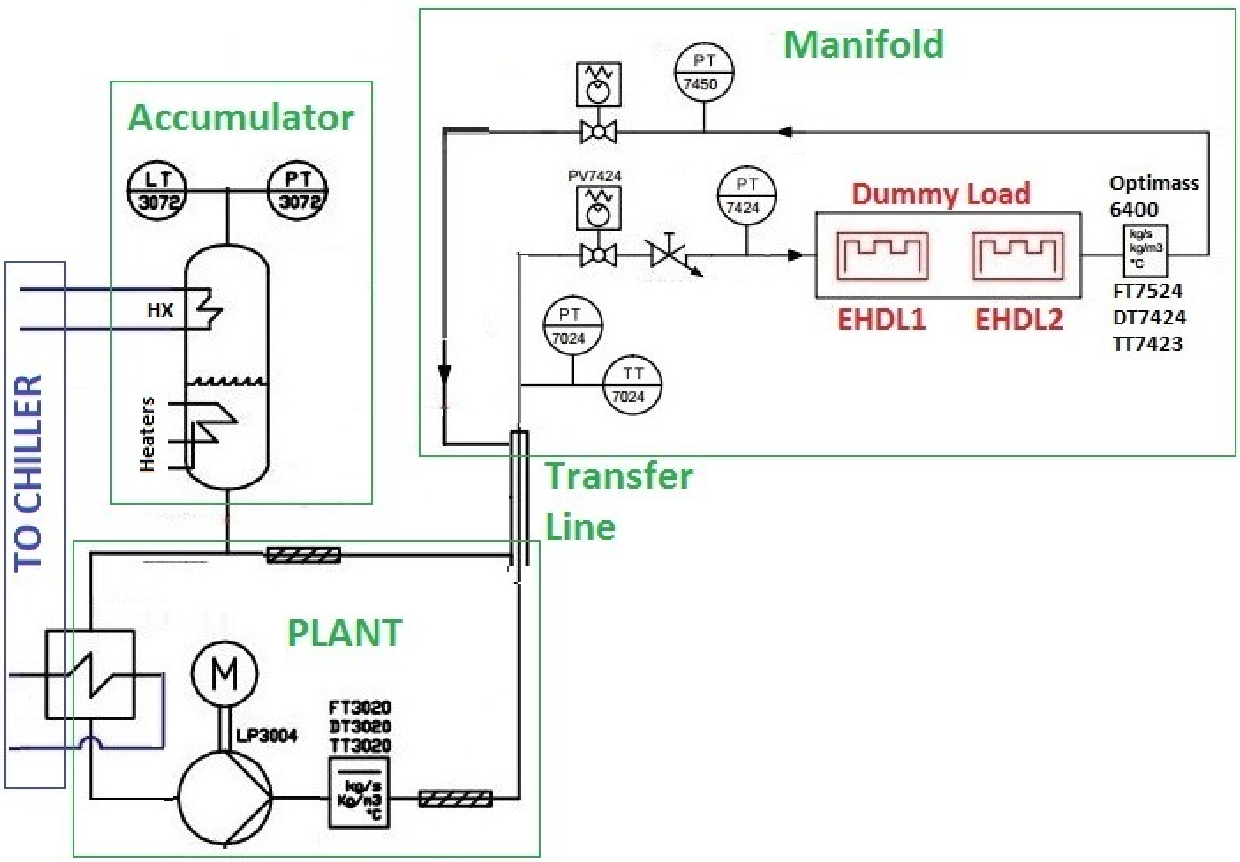
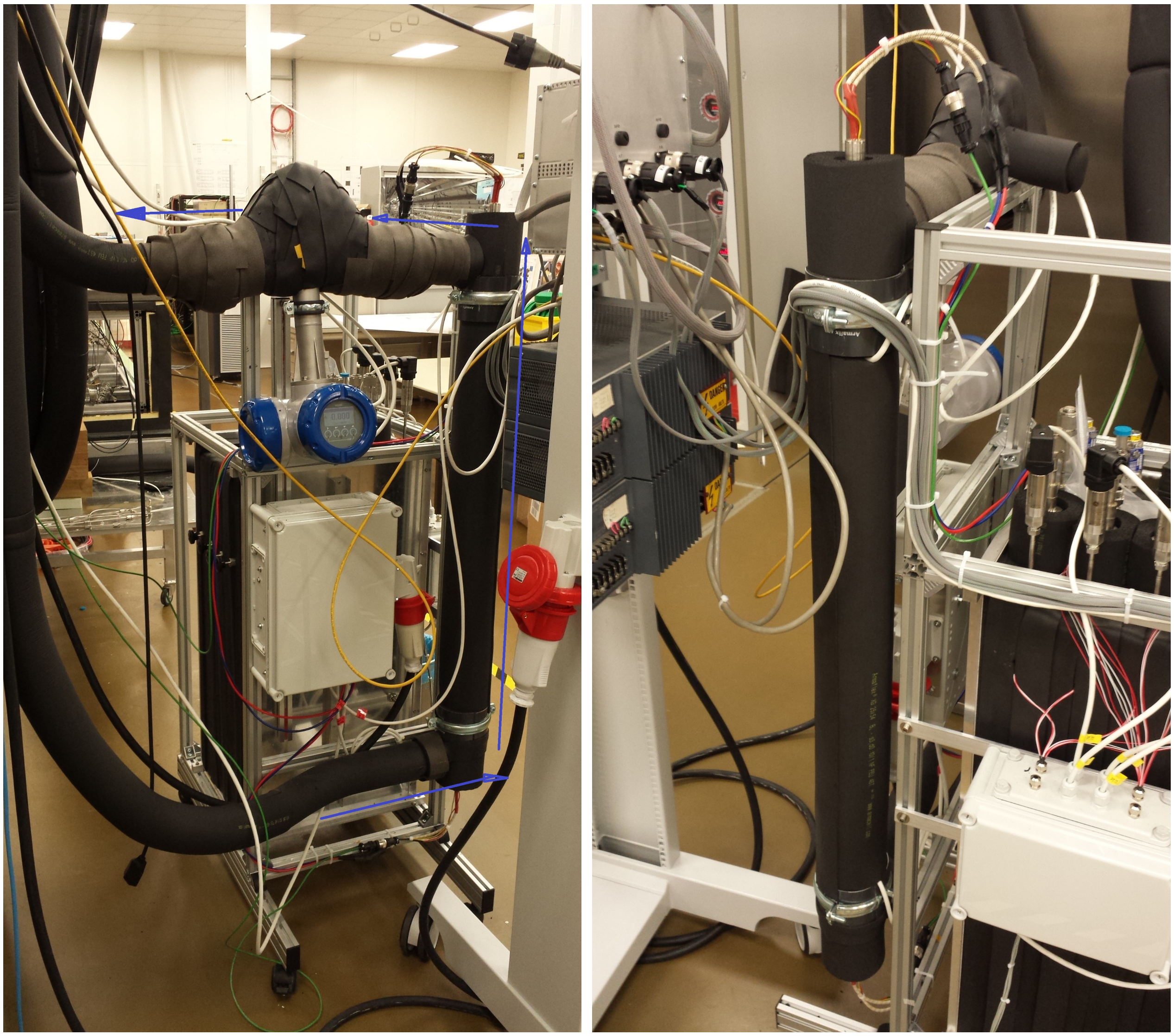


Figure 3.2: A simplified process and instrumentation diagram of the TIF cooling plant in the configuration relevant to the tests, displaying only relevant instrumentation. A diagram of the whole TIF if given in appendix A



(a) Front view. (b) Side view.

Figure 3.3: Photographs of the Optimass sensor connected to the dummy load heating section. The direction of flow is given by the blue arrows.

- meaning hundreds of thousands of data points over the 3-week test campaign. The Optimass sensor was configured by Krohne Italy to deliver mass flow, density and temperature signals through a 4-20 mA bus in the following measurement ranges:

- Mass Flow Rate: 1.4-115 g/s
- Density: 100.6 - 1200 kgm^{-3}
- Temperature: ????

The sensor was cabled to the same PLC controlling TIF and logging all of its instrumentation, and the signals were mapped to the values configured by Krohne. This approach streamlined control and post-processing by consolidating the plant, heaters and instrument on a single Scada interface, and logging the data in a single location at common timesteps.

3.1.3 Variables and Assumptions

The instrument's performance was to be assessed in relation to three independent variables:

- Coolant temperature - regulated by the accumulator set point.
- Mass flow rate - set by the pump speed and stroke.
- Heat Load - set by the heaters' rms current.

The coolant temperature set point determines the position along the vapour dome on a P-h diagram of the 2PACL cycle, and therefore the local pressure in the instrument. This influences the evaporative behaviour of the coolant, as well as the vapour quality for a given density. While a wide range of temperature was to be explored, the invariance of the temperature during a tests was an essential control variable.

The mass flow rate was set by the speed and stroke of the pump, but not regulated during tests. This meant that as the vapour quality of the coolant increased, the resultant increase in pressure drop decreased the effective flow rate for given pump conditions. The resulting fluctuations in true flow rate affect the trends plotted by nominal flow rate, but because flow rate is measured in real time, they did not effect error signal calculations.

The dummy load heaters are resistive cartridge heaters, whose power is controlled by pulse width modulation. The user specifies a Watt value on the Scada interface, and the PLC applies the correct PWM signal to achieve the demand power output. Heater control is open-loop, but their performance has been validated in the past.

Key Variables and Settling Times		
Variable	**Control Method**	**Settling Time**
Temperature	Accumulator Set Point	30-90 minutes
Mass Flow Rate	Pump speed and stroke	15-30 minutes
Vapour Quality	Dummy Load Power	5-15 minutes

Table 3.1: Key variables, their control method and their settling times.

A broad range of all three variables was explored. But because this experiment sought only to evaluate steady-state performance, transient data was to be minimised. The control variables were therefore closely monitored to minimise fluctuations.

3.1.4 Test Protocol

Before beginning 2-phase testing, the instrument's calibration was validated in pure liquid by comparing its readings of mass flow, density and temperature with a reference instrument on the plant (FT3020) for a range of flow rates and temperatures.

For 2-phase testing, a test protocol was developed to ensure consistency of data. A change to any of the independent variables caused a significant transient response. But the process of fine-tuning the values and waiting for their response to settle differed for each variable. Tests were designed accordingly.

Altering test conditions employed a nested approach. First, the coolant temperature was set in the accumulator. Then various heat loads were applied at a given pump speed to explore a range of vapour qualities at a given flow rate, before changing the pump conditions. A typical test segment: various heat loads at a given flow rate and temperature, is shown in Figure 3.4.

3.2 Data Analysis Methods

A method, summarised in Figure 3.5, was devised for the export, pre-processing and process of data. This approach filtered through the hundreds of thousands of data points to reach a small subset of steady-state data during test conditions.

Figure 3.4: A typical test. The steps in heat load are shown as vertical red lines.

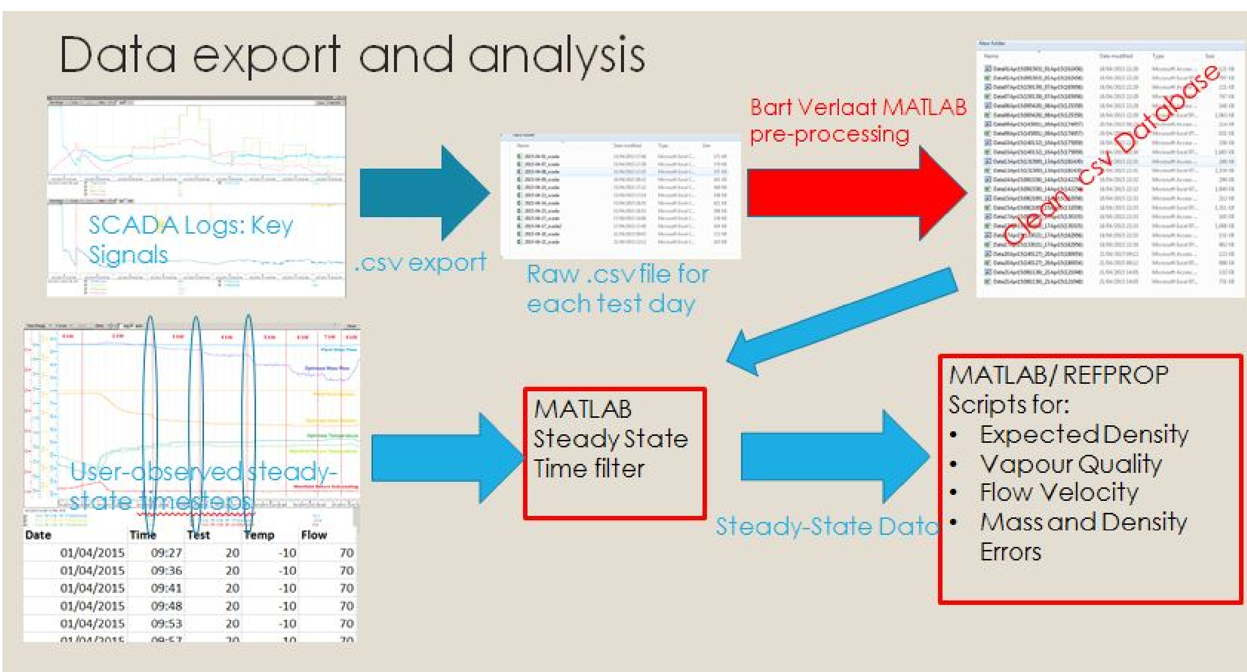


Figure 3.5: A summary of data processing and analysis.

Key Signals			
Signal Type	**Signal Name**	**Thermodynamic Symbol**	**Description**
	FT7524	$\dot{m}$	Mass flow rate measured by Optimass 6400
Optimass	DT7424	ρ_5	Density measured by Optimass 6400
	TT7424	T_5	Temerature measured by Optimass 6400
Reference	FT3020	$\dot{m}_{ref}$	Liquid mass flow rate measured in plant.
Reference	PT7024	P_3	Manifold supply pressure.
Reference	TT7024	T_3	Manifold supply temperature.
Reference	EHDL1	$\dot{Q}_a$	Dummy load heater 1 power.
Reference	EHDL2	$\dot{Q}_b$	Dummy load heater 2 power.
Reference	PT7450	P_5'	Pressure at instrument discharge.

Table 3.2: Key Signals

3.2.1 Export Pre-Processing

Including time, 12 signals out of the dozens logged in the PLC were identified as being key for this study. These are summarised in table 3.2.

A page of plots tracking these signals was created in the Scada interface. Then, *.csv* data for each signal was exported by navigating to the time of a given test and exporting a 4 hour window of data. These *.csv* files for each day of testing were then pre-processed using modified MATLAB scripts developed by Bart Verlaat. Pre-processing involved merging the data from each test into a single database, handling empty cells and overlapping timesteps, and saving the cleaned data in a new database to be called by MATLAB.

3.2.2 Data Processing and Visualisation

With the key signals filtered to leave only steady state conditions, these were processed to assess the sensor's performance. The sensor was evaluated by comparing its readings to a combination of reference instrumentation and analytically computed reference conditions.

Analysis employed an theoretical MATLAB model to compute thermodynamic state variables in the sensor, and called a refrigerant simulation program called REFPROP to compute the local conditions of interest. REFPROP, developed by National Instruments, is a widely used program that simulates refrigerant performance using a combination of analytical and empirical methods.

3.2.3 Calculation of Reference Conditions

The local density and vapour quality in the Optimass sensor are calculated using the local pressure and specific enthalpy. A pressure and an enthalpy give the fluid's exact location in the vapour dome, and the vapour quality and density can be read from the chart, as shown in Figure **??**. This is implemented using REFPROP. With the following syntax:

Q = refpropm('Q','P',$< P_5$ *[kPa]*$>$ *, 'H',* $< h_5$ *[J/kg]*$>$ *, 'CO2')*

The local enthalpy at the sensor, h_5, is given by the sum of the manifold inlet enthalpy, h_3 and the change in enthalpy due to the heat load, Δh.
h_3 is determined with REFPROP from the inlet manifold inlet conditions (Pressure and Temperature in pure liquid), while the change in enthalpy is calculated from the heat load and reference mass flow rate.

h_3*=refpropm('H','P',*$< P_3$ *[kPa]*$>$ *,'T',* $< T_3$ *[K]*$>$*, 'CO2')*

p = Heat Load [W]

$$\Delta h = \frac{p}{\dot{m}} \tag{3.1}$$

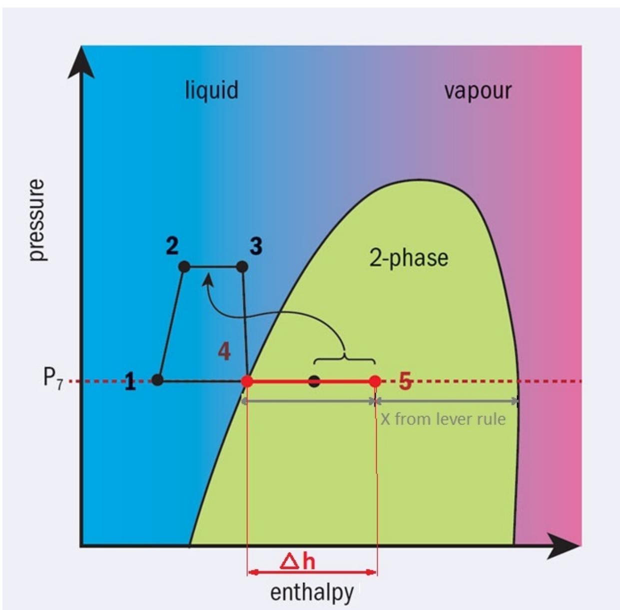


Figure 3.6: The analytic model for calculating local 2-phase conditions at the flow meter.

4. Results

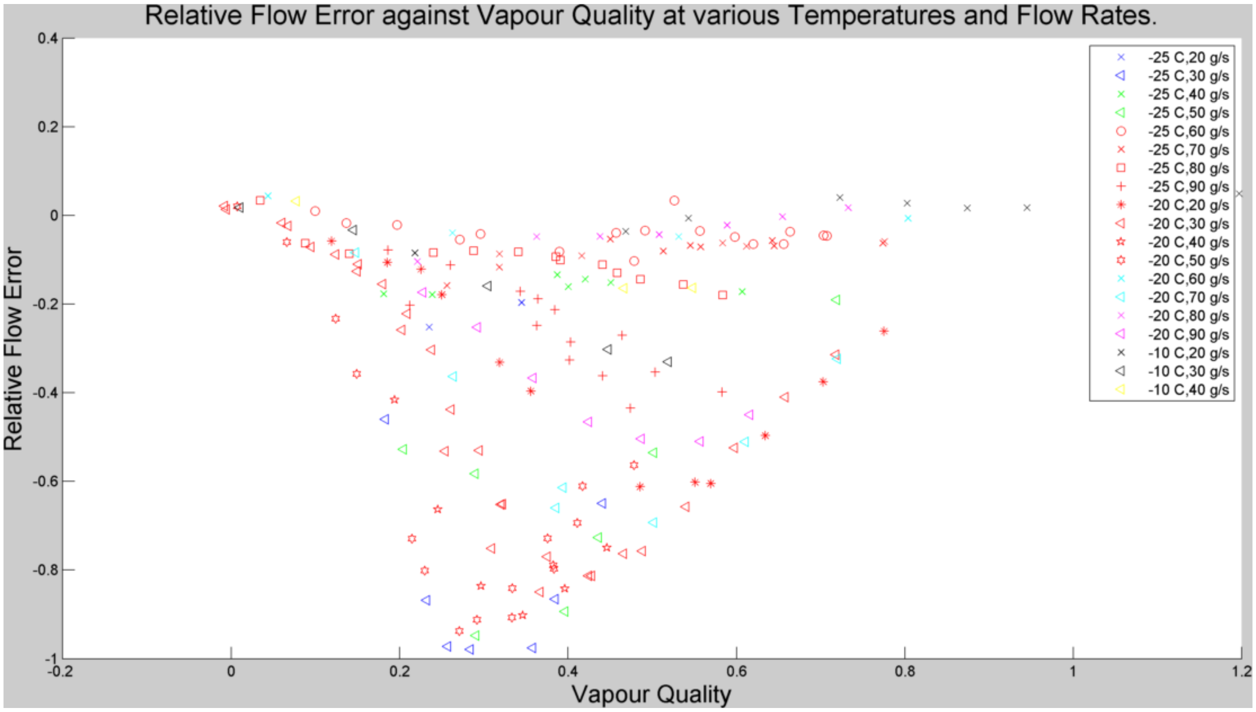


Figure 4.1: An overview of relative mass flow error against vapour quality.

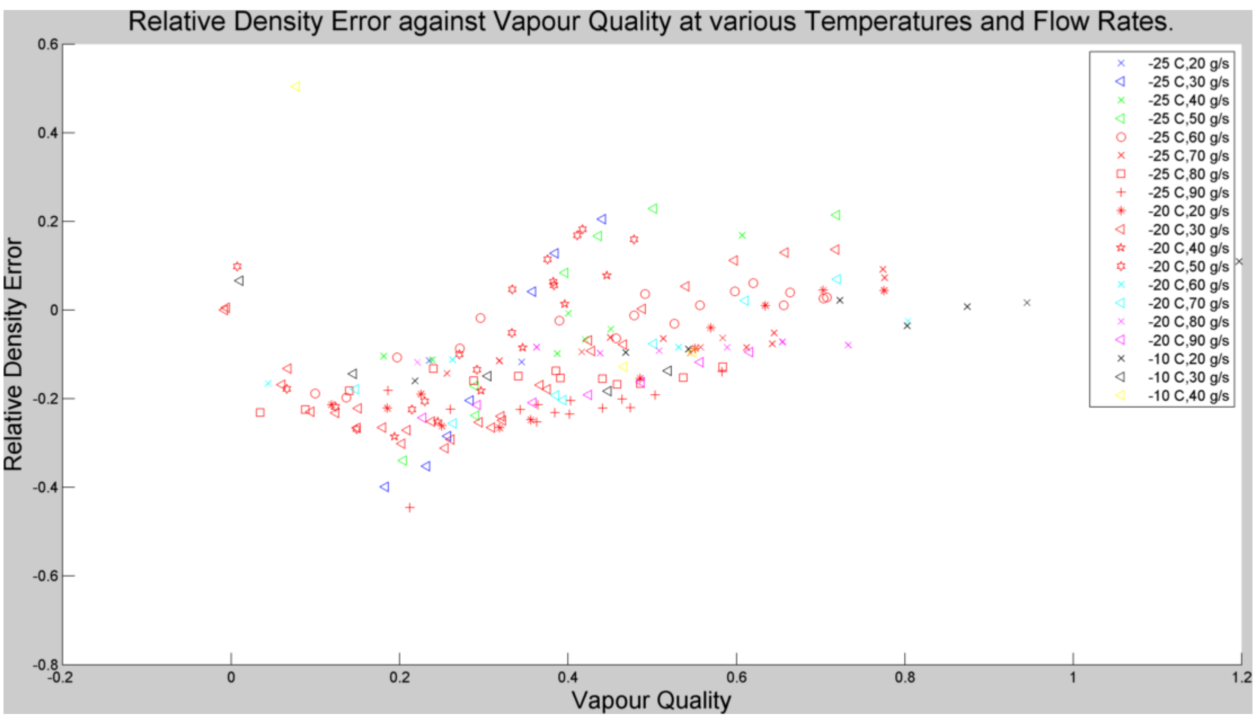


Figure 4.2: An overview of relative density error against vapour quality.

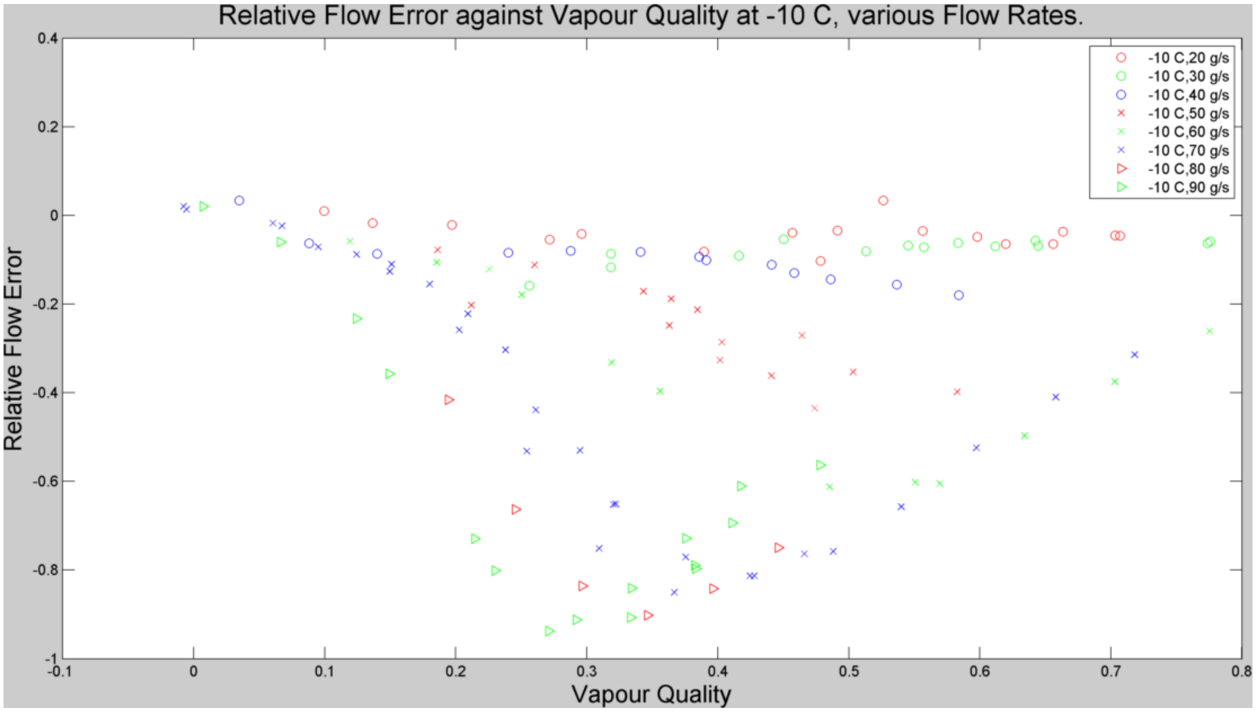


Figure 4.3: An overview of relative density error against vapour quality.

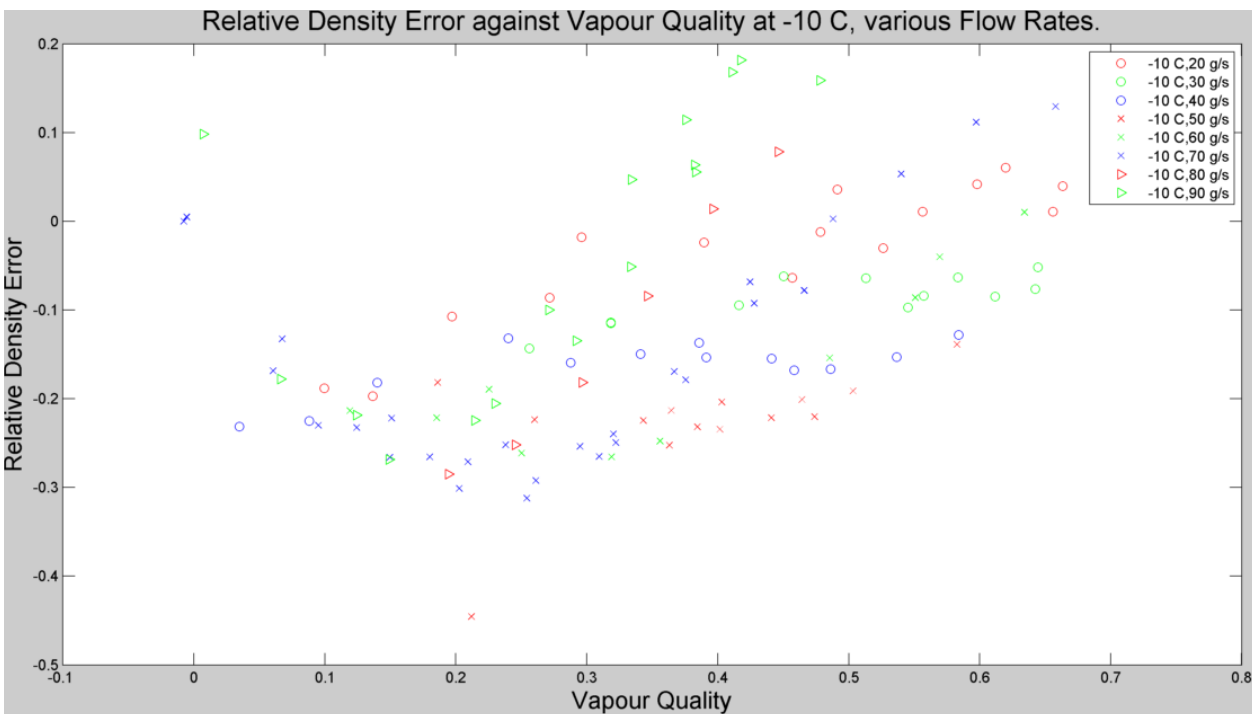


Figure 4.4: An overview of relative density error against vapour quality.

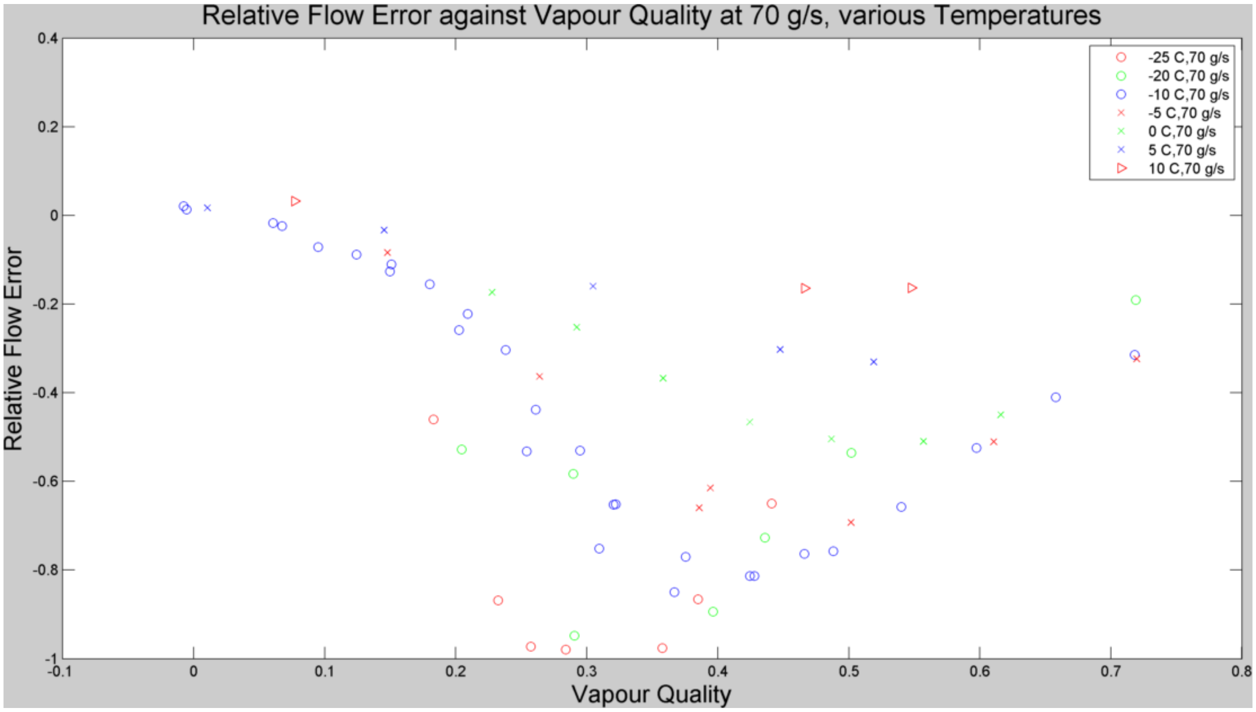


Figure 4.5: An overview of relative density error against vapour quality.

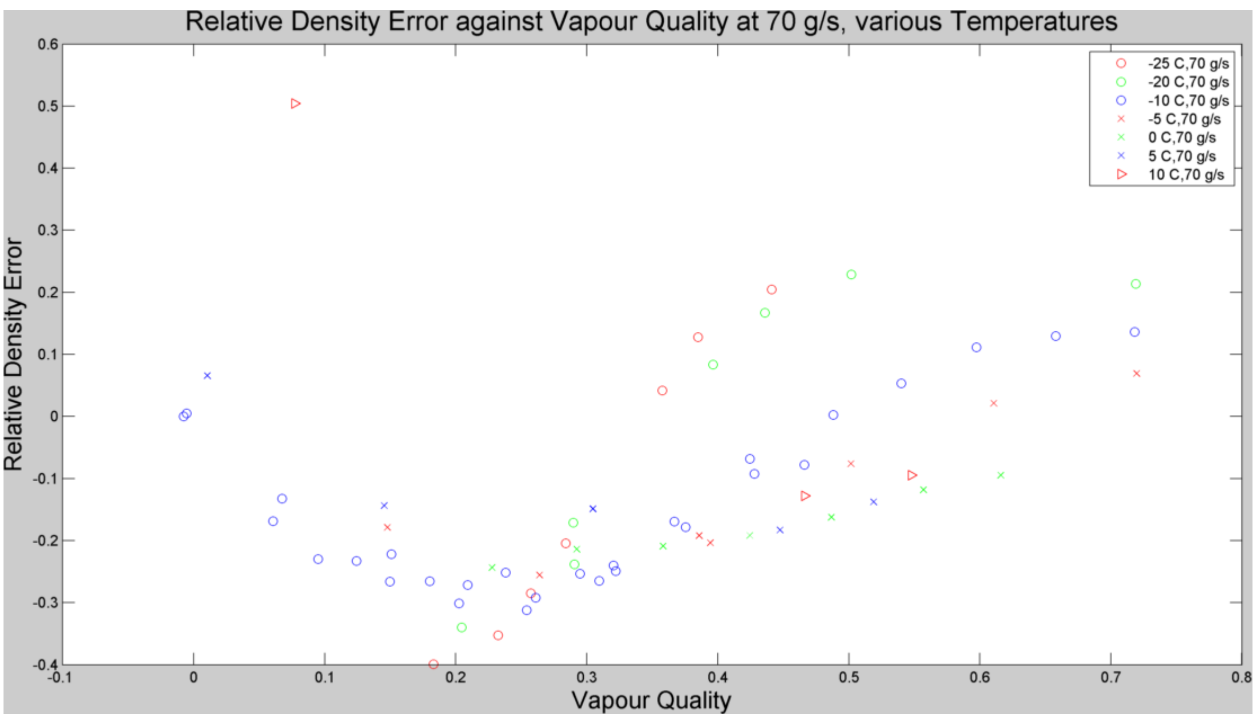


Figure 4.6: An overview of relative density error against vapour quality.

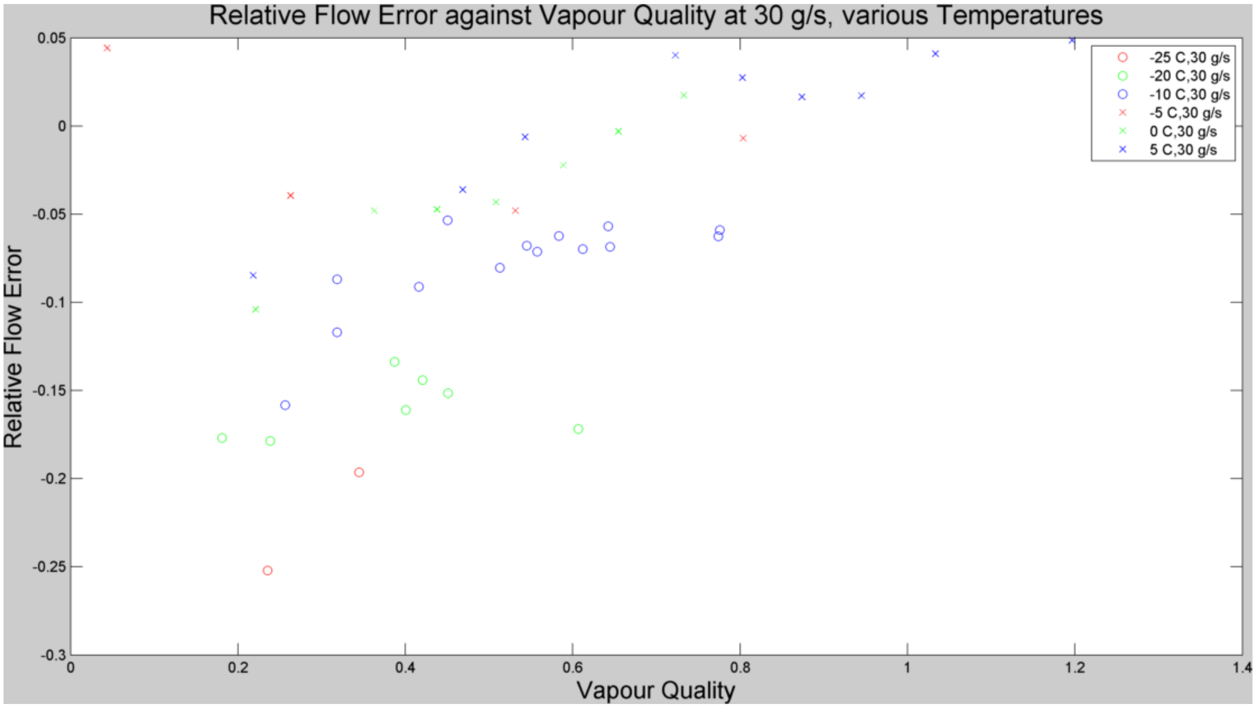


Figure 4.7: An overview of relative density error against vapour quality.

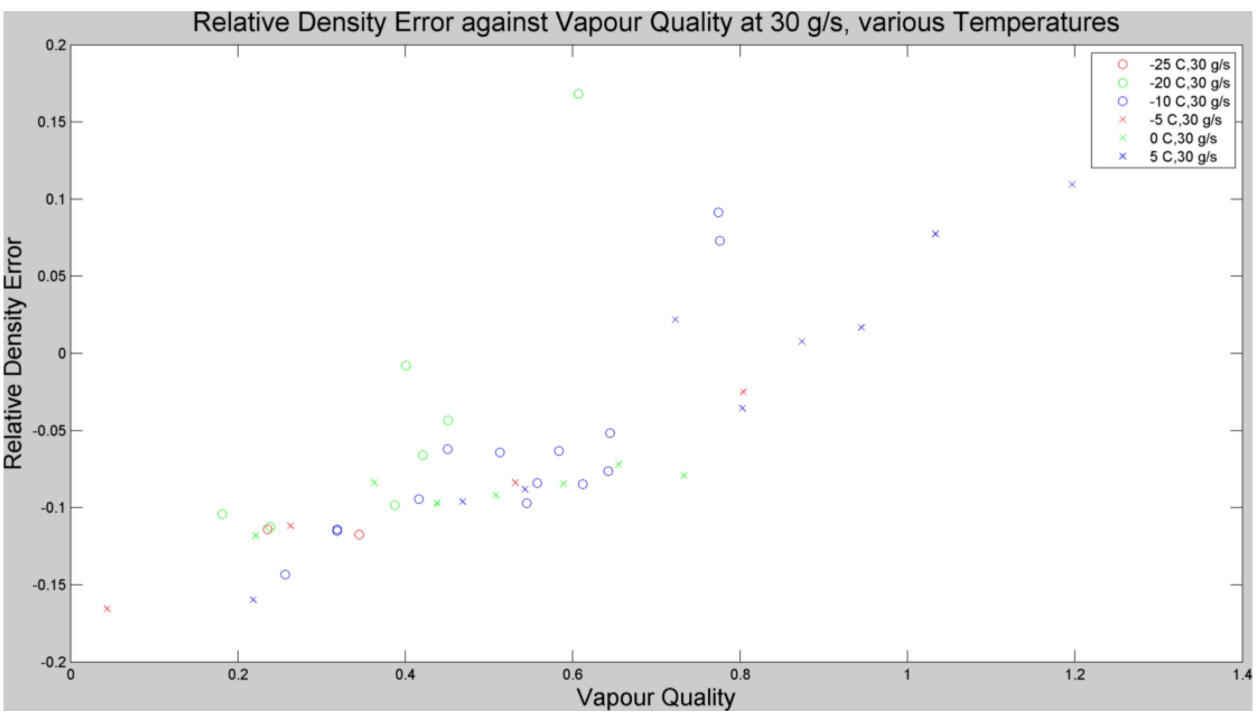


Figure 4.8: An overview of relative density error against vapour quality.

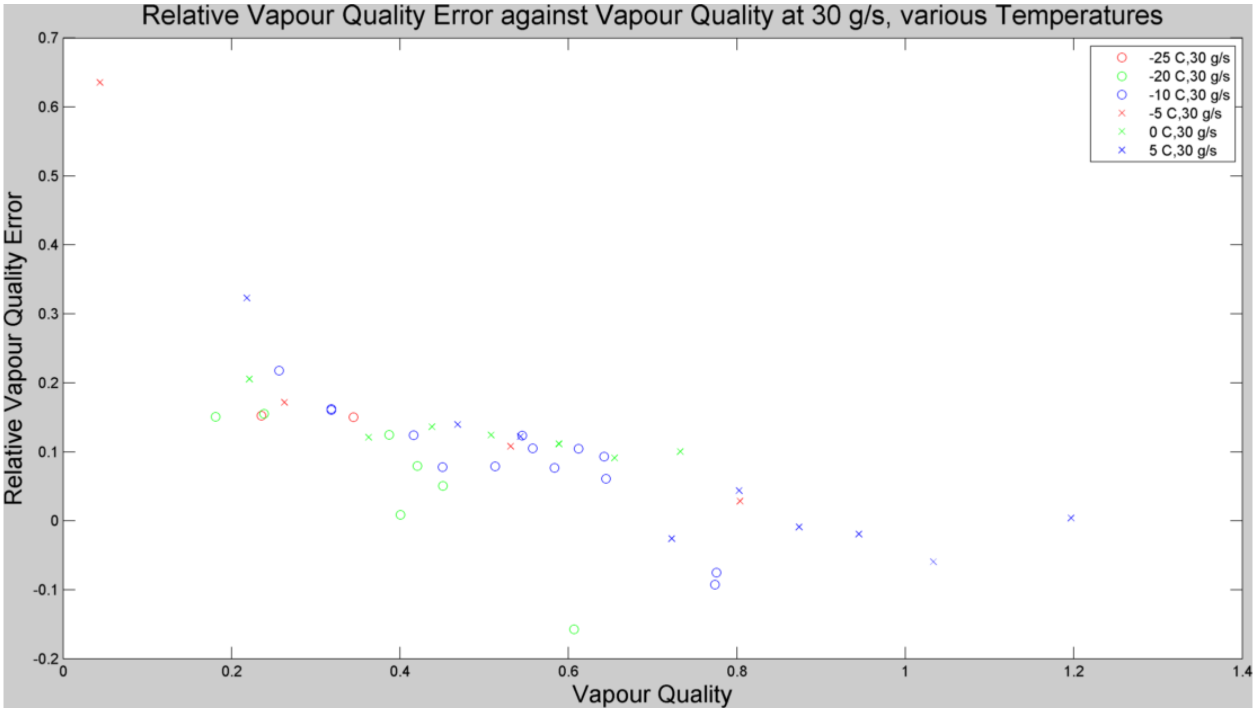


Figure 4.9: An overview of relative density error against vapour quality.

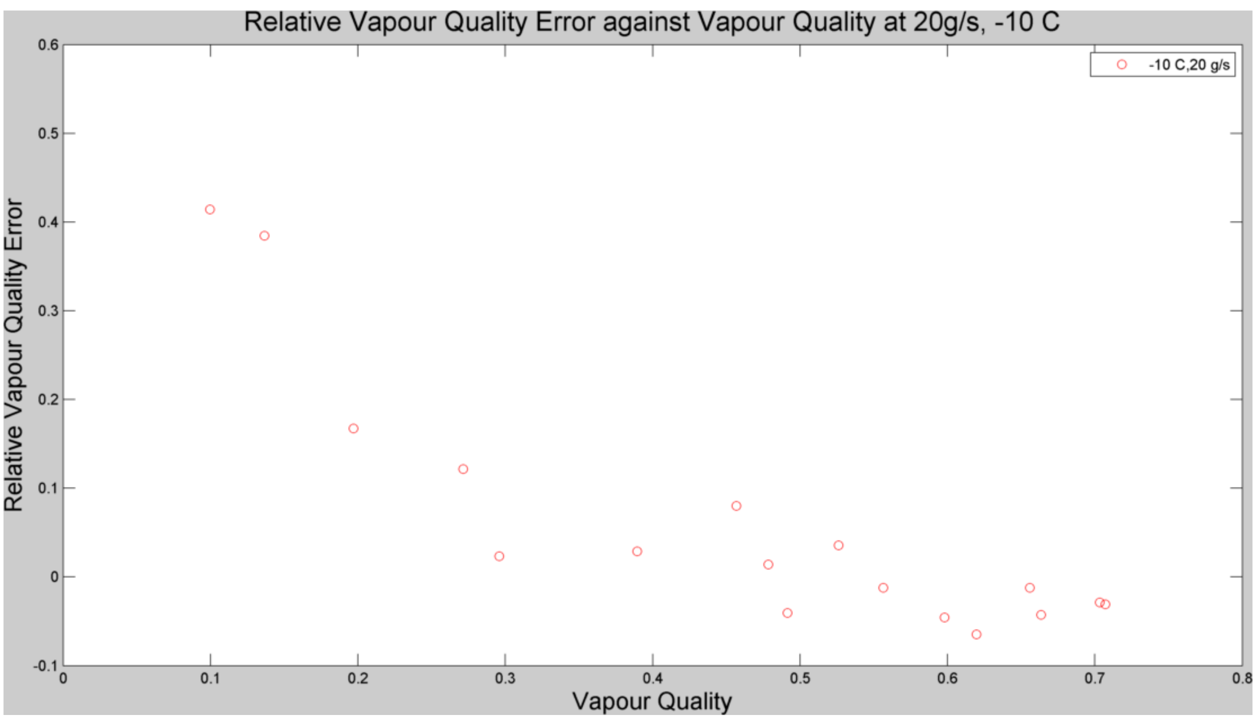


Figure 4.10: An overview of relative density error against vapour quality.

5. Discussion

6. Conclusions

7. Future Work

larger flow meter, dedicated test rig, volumetric flow rate of gas phase? flow regimes, frequency domain analysis, flow meter positioning. real time reference condition calculation. flow velocity. test low flows using bypass. chiller management. definition of true performance envelope.two-phase signal what does it mean?

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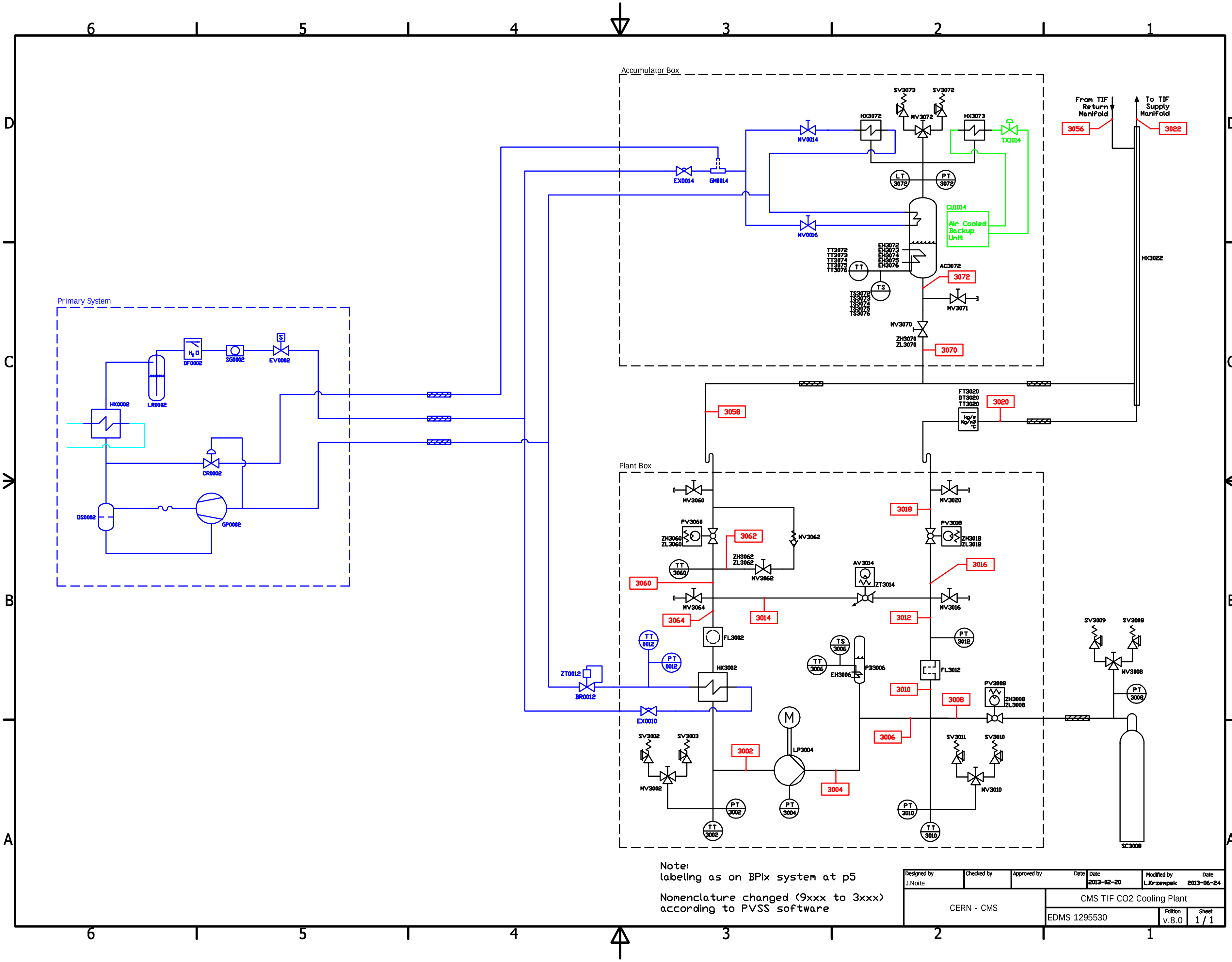
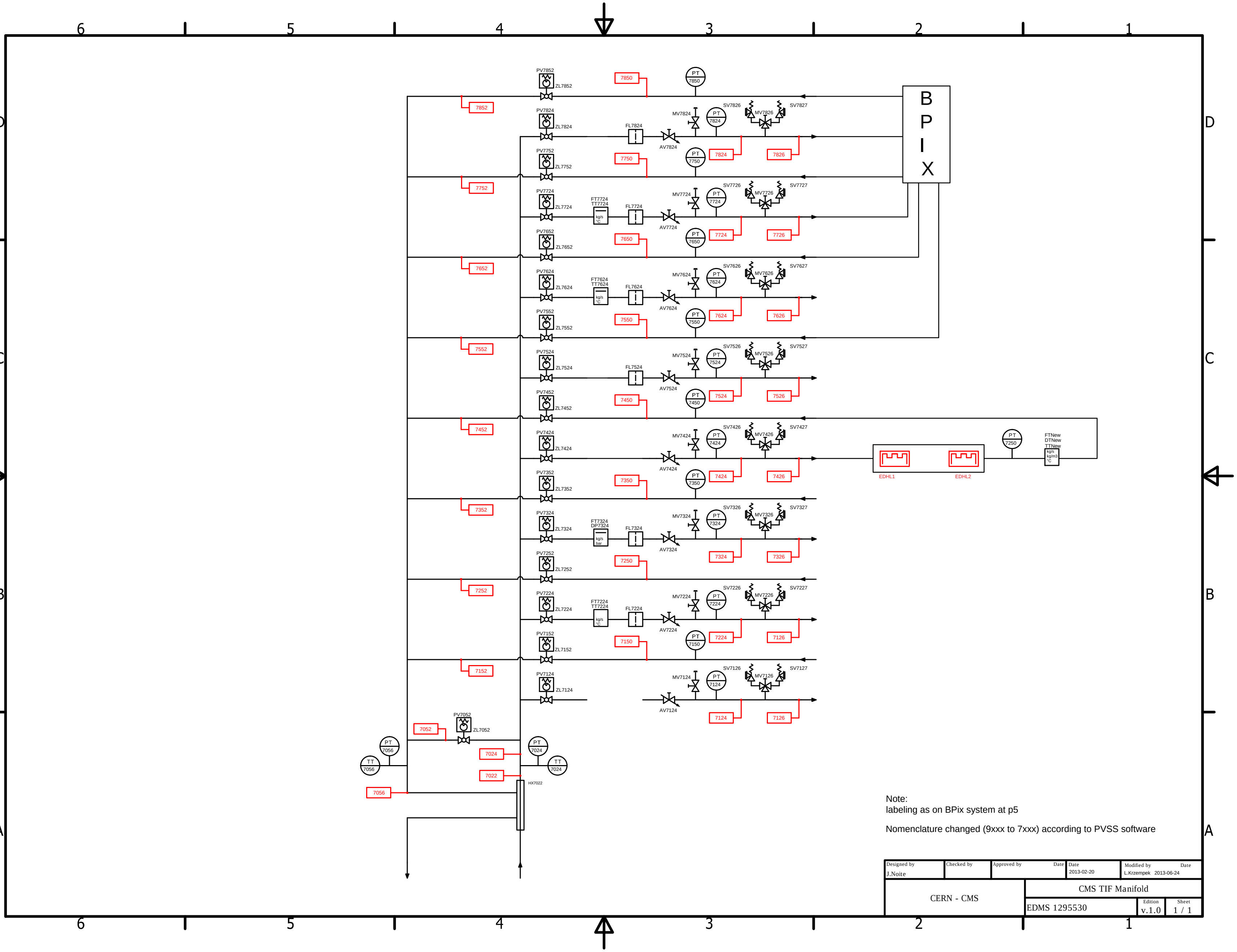
A. The TIF Cooling System


Primary System
Accumulator Box
Plant Box
From TIF Return Manifold
To TIF Supply Manifold
Air Cooled Backup Unit
Note:
labeling as on BPix system at p5
Nomenclature changed (9xxx to 3xxx) according to PVSS software
Designed by J.Noite
Checked by
Approved by
Date 2013-02-20
Modified by L.Krzempek
Date 2013-06-24
CERN - CMS
CMS TIF CO2 Cooling Plant
EDMS 1295530
Edition v.8.0
Sheet 1 / 1



Note:
labeling as on BPix system at p5

Nomenclature changed (9xxx to 7xxx) according to PVSS software

Designed by	Checked by	Approved by	Date	Date	Modified by	Date
J.Noite				2013-02-20	L.Krzempek	2013-06-24

CERN - CMS	CMS TIF Manifold		
	EDMS 1295530	Edition v.1.0	Sheet 1 / 1

B. Krohne Calibration and Sizing Documents

OPTIMASS 6000 - H 08

KROSS Sizing 2014-12-18

Project

Project	cern

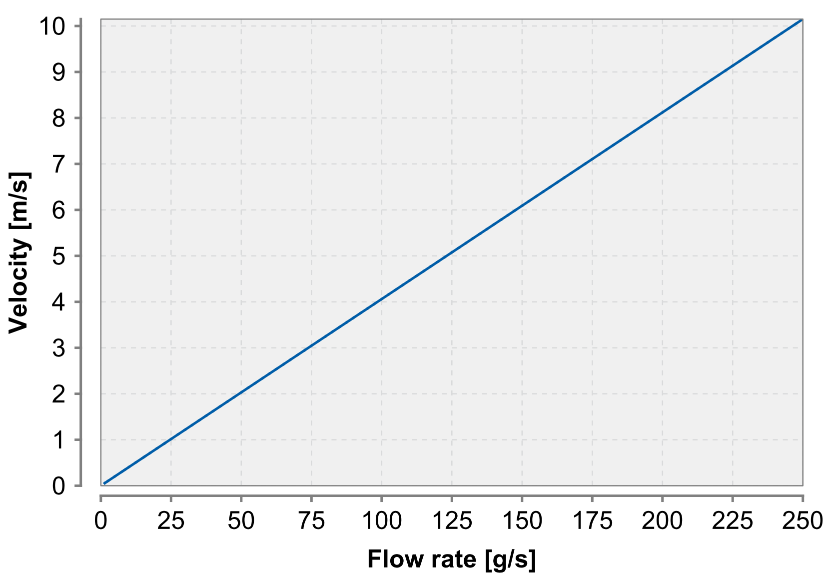
Fluid

Aggregate state	Formula	Fluid
liquid	CO2	Carbondioxide (liquid)

Process data

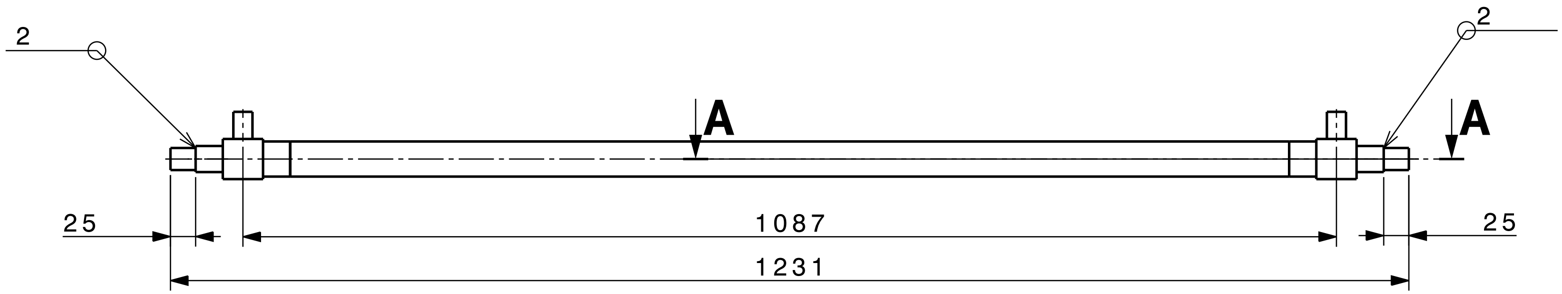
	Minimal	Nominal	Maximal	Unit	
Density (operational)		1.005		kg/l	
Viscosity		0.128		mPa.s	
Temperature		-15.0		°C	
Pressure (gauge)		20.0		bar	
Flow rate	1.4	30.0	250.0	g/s	(Mass)

Velocity

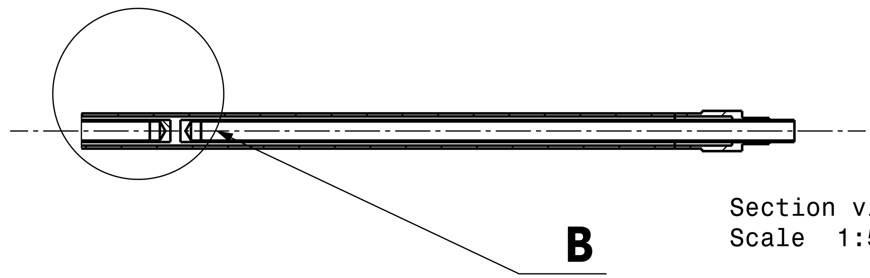


Flow rate [g/s]	Velocity [m/s]
1.389	0.0564
1.4	0.0568
20.0	0.812
30.0	1.218
45.0	1.827
72.5	2.943
100.0	4.06
127.5	5.176
155.0	6.293
182.5	7.409
210.0	8.526
237.5	9.642
250.0	10.15

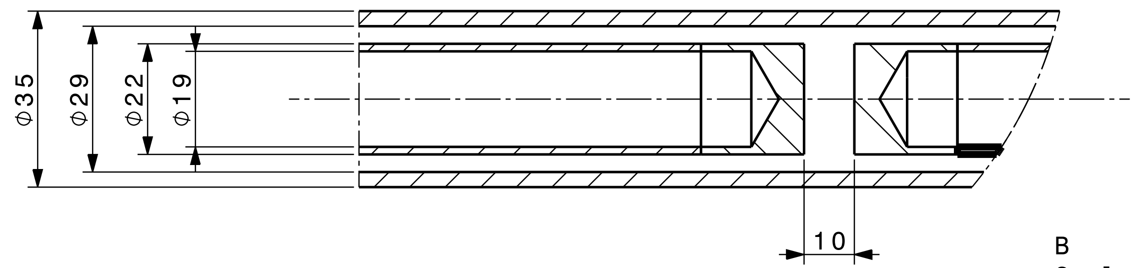
C. Dummy Load Heater Module Mechanical Design



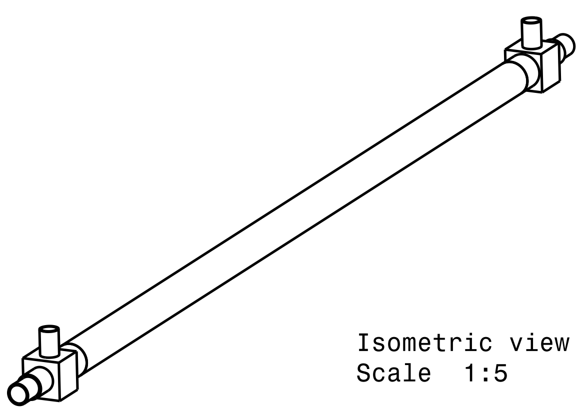
Front view
Scale 1:5



Section view A-A
Scale 1:5



B
Scale 1:1



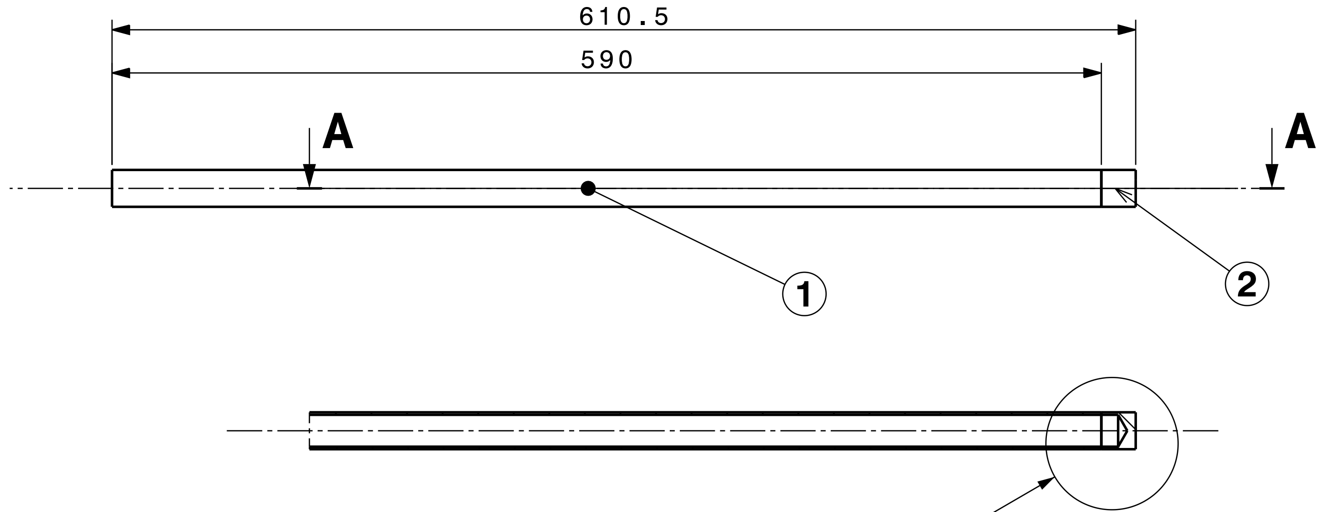
Isometric view
Scale 1:5

QUANT.	DESCRIPTION	POS	MAT.	OBSERVATIONS	REF.CERN
2	Heatre pipe	3			
1	CO2 pipe	2			
2	TEE	1			

ENS/ASS	S.ENS/S.ASS	
NEW HEATER DESIGN	ECHELLE SCALE	DES/DRA. T. KATOPODIS 2013-09-25
		CONTROLLED
		RELEASED
		APPROVED
		\\
		REMPLACE/REPLACES
NON VALABLE POUR EXECUTION NOT VALID FOR EXECUTION	QAC -	SIZE 3 IND.

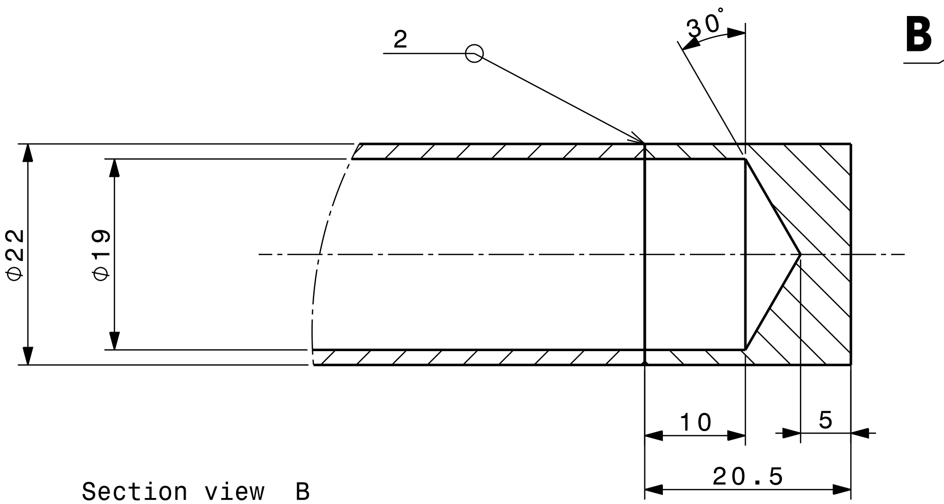
DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION



Front view
Scale 1:3

Section view A-A
Scale 1:3



Section view B
Scale 2:1

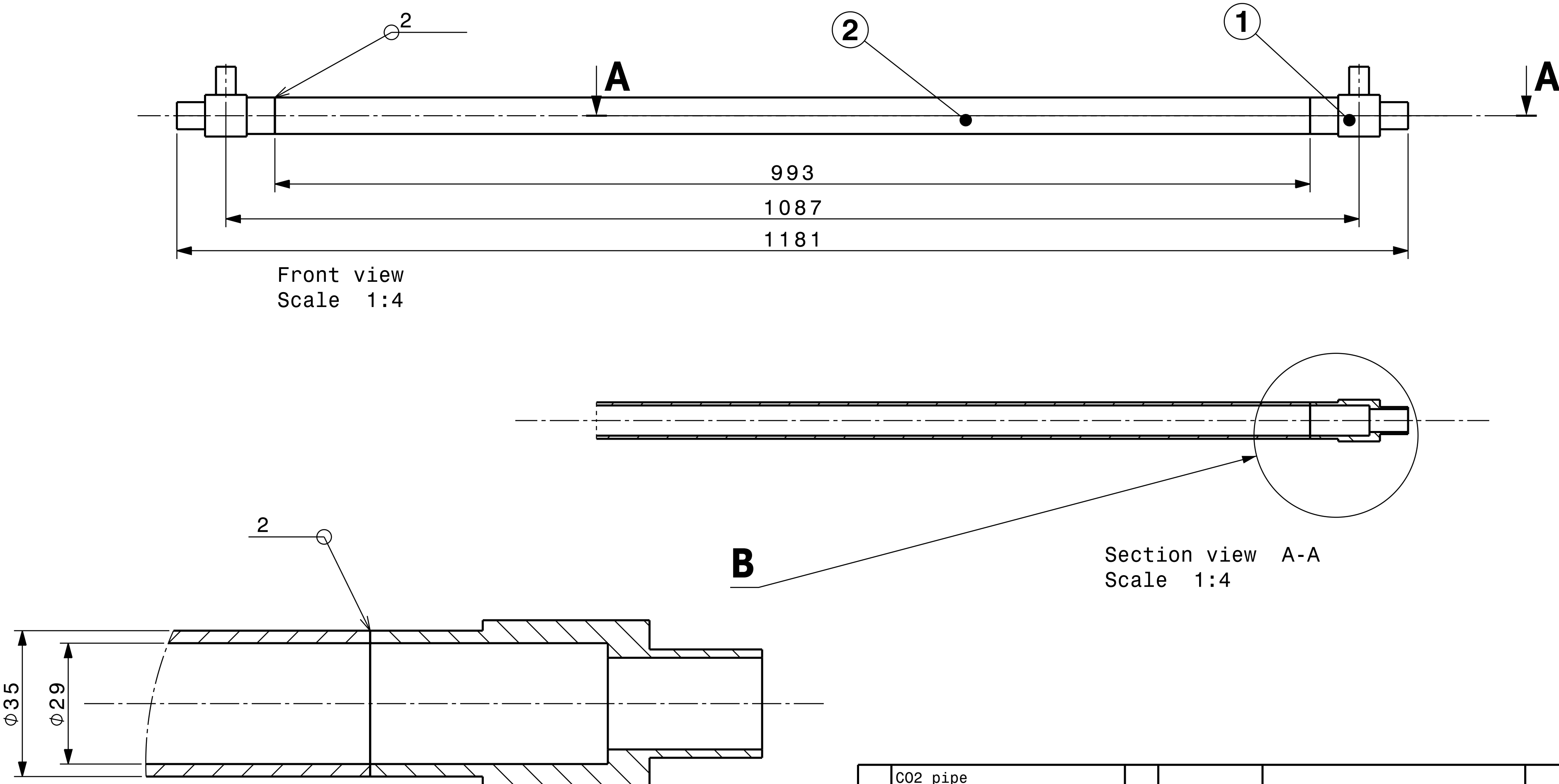
QUANT.	DESCRIPTION	POS	MAT.	OBSERVATIONS	REF.CERN
1	Heater tube cap	2			
1	Heater tube	1			

ENS/ASS		S.ENS/S.ASS		
HEATER PIPE	ECHELLE SCALE	DES/DRA.	T. KATOPODIS	2013-09-25
		CONTROLLED		
		RELEASED		
		APPROVED		
		\\		
		REMPLACE/REPLACES		
NON VALABLE POUR EXECUTION NOT VALID FOR EXECUTION	QAC -		SIZE 3	IND.

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE



Front view
Scale 1:4

Section view A-A
Scale 1:4

Section view B
Scale 1:1

QUANT.	DESCRIPTION	POS	MAT.	OBSERVATIONS	REF.CERN
1	CO2 pipe	2			
2	TEE	1			

ENS/ASS — S.ENS/S.ASS

CO2 PIPE WELDED ON TEE

ECHELLE SCALE			
DES/DRA.	T. KATOPODIS	2013-09-25	
CONTROLLED			
RELEASED			
APPROVED			
	\\		
REMPLACE/REPLACES			

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC		SIZE	IND.
-		3	

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

D. MATLAB Code

E. Raw Data