SCARABEUS

A H2020 Research and Innovation Action project, Grant Agreement number 814985

D4.3 – Heat transfer in the air-cooled condenser

This Deliverable 4.3 report is part of a project than has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 814985

WP 4: Air-cooled condenser and heat exchanger development

Task 4.3: Heat transfer characterisation of the air-cooled condenser

Version: final version, July 8th 2021

Technical References

Deliverable No.	4.3 – Public report on the heat transfer characteristics using CO_2 blends
Dissemination level [1]	PU
Work Package	4: Air-cooled condenser and heat exchanger development
Task	4.2: Heat transfer characterisation of the air-cooled condenser
Lead beneficiary	KELVION
Contributing beneficiary(ies)	TUW
Due date of deliverable	31st December 2020 (delayed to June 30th communicated early January)
Actual submission date	08 July 2021

[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

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History of Changes

Version	Date	Changes
1	20/06/2021	Original version created by Pierre-Luc David
2	05/07/2021	New version implementing comments sent by Giampaolo Manzolini
Final	08/07/2021	Approved by Giampaolo Manzolini

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Nomenclature/Acronyms

Parameter	Unit	Description
H	$(W.m^{-2}.°C^{-1})$	Global heat exchange coefficient
R	$(m^2.°C^1/W)$	Global thermal resistance
Re	$(m^2.°C^1/W)$	External resistance
Rf	$(m^2.°C^1/W)$	Fouling resistance
Ri	$(m^2.°C^1/W)$	Internal resistance
Rt	$(m^2.°C^1/W)$	Tube resistance

AFC : Air Fin Cooler or Air Cooled Heat exchanger or Fin Fan Cooler or Air Cooled condenser
CO_2 : Carbon Dioxide
DIESTA : Dual Internally and Externally Structured Tube for Air coolers
HTRI : Heat Transfer Research, Inc®
sCO_2 : Supercritical Carbon Dioxide
TC : Thermocouple
TUW : Technische Universität Wien
WP4 : Work Package 4

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Executive summary

The purpose of the document is to describe the developed methodology to determine the condensing and cooling correlation of CO_2 and blended CO_2 to optimize the sizing of the Air cooled condenser for SCARABEUS project.

An experimental test rig located at TUW (Technische Universität Wien) has been upgraded and commissioned in order to evaluate the thermal and hydraulic performance of internally smooth and enhanced tubes in CO_2 cooling and CO_2 condensing mode.

The data reduction is based on local measurements of the wall temperatures, the cooling medium in the annulus and the CO_2 inside the tube.

The first section of the document is dedicated to the literature review of inner groove enhancement in general and specially for the CO_2. The goal is to define the geometry of the groove inside the tube. Two geometries are designed: one devoted to the cooling of the CO_2. The second one to its condensation.

The second section defines the design and the manufacturing of the test sections.

The last section discusses the results of the test section and they are compared to the correlation found in literature for smooth tube.

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Literature check / Investigation

1 Introduction

Kelvion has the lead of the work package 4 for the SCARABEUS project. The WP4 consist, to the suppling of the condenser to cool and condense the mixture of the CO_2 and the CO_2-blend in test rig at TUW. It will be performed by using an Air Fin Cooler (AFC).
An AFC or Air Cooled Heat exchanger or Fin Fan Cooler or Air Cooled Condenser is a heat exchanger that use the ambient air as a cooling media to cool and/or to condense a process fluid (liquid or gas).
It is composed of a supporting structure, headers to disseminate and collect the fluid, a bundle with several rows of fins tubes where the fluid flows, fan and drive systems.

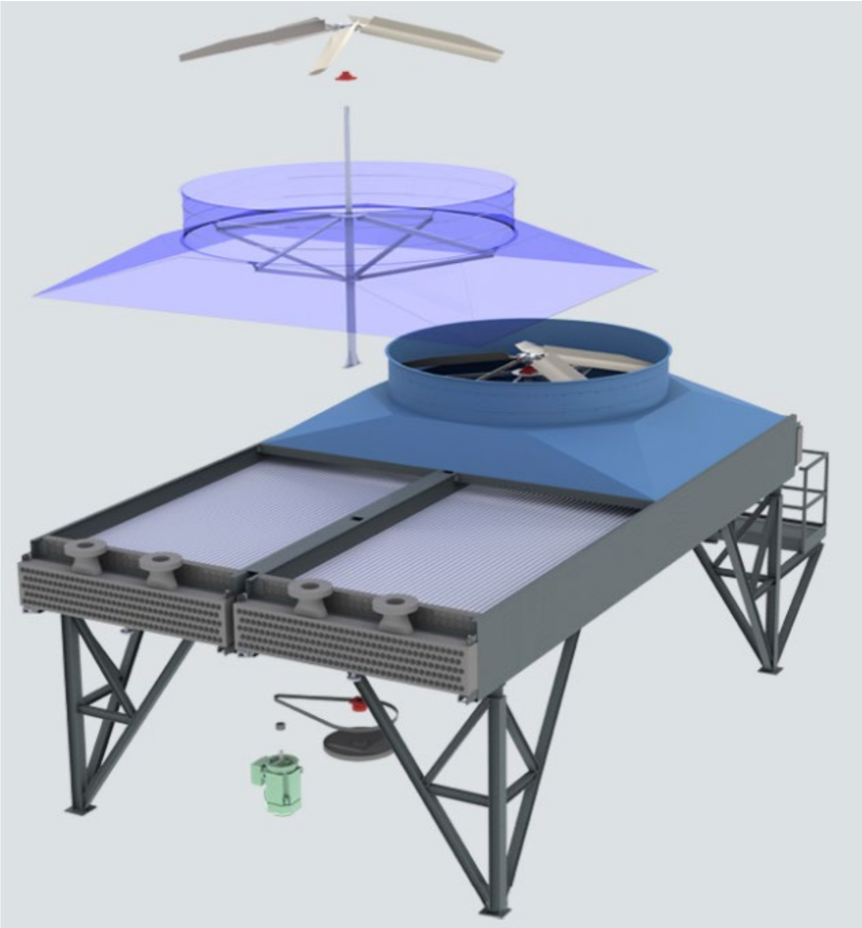

Figure 1: AFC with induced draft.

The AFC can be manufactured with forced draft (fan below the bundle) or induced draft (fan above the bundle).
To optimize the size of the AFC, DIESTA tube technology is used. This report deals with the methodology used to define the geometry of the internal groove of the tube, the manufacturing of the tube and the result of the test performed at the TUW test rig.

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2 Methodology

This paragraph is dedicated to the internal enhancement factor for the SCARABEUS project. It begins with a thermal reminder to describe the parameter that need to be enhanced to increase the global heat coefficient. It continues with a brief description of the external enhancement follows by the internal enhancement and the description of the best inner groove geometries.

2.1 Thermal reminder

The global heat exchange coefficient (H) depends on the tube technology and for the AFC on the fan energy consumptions. To avoid an increase of the energy consumption, it is possible to increase the heat exchange coefficient.
The higher the coefficient, the easier the heat is transferred from its source to the cooling fluid. Increasing the coefficient H allows reducing the heat surface area and consequently the cost of the heat exchanger.
It is defined by the following formula:

$$H = \frac{1}{R}$$

R is the global thermal resistance. It is the sum of the internal resistance (Ri), the external resistance (Re), the tube resistance (Rt) and the fouling resistance (Rf).

$$R = Ri + Re + Rt + Rf$$

The tube resistance is due to the metal thermal conduction. It is only linked to the material of the tube. The fouling resistance only depends of the fluid. These two parameters cannot be improved.

To increase the heat transfer, the resistance Ri and Re should be reduced. The improvement of Re and Ri has been performed by Kelvion several years ago for the AFC. The patented technology so called Groovy fin and the technology DIESTA (see Figure 2) is two of the Kelvion expertise.
The improvement of the Ri, dedicated to sCO_2 application, is the task of the WP4.2. The first part of the study is to define the best geometry of the inner groove for the CO_2 for the condensation and for the cooling.

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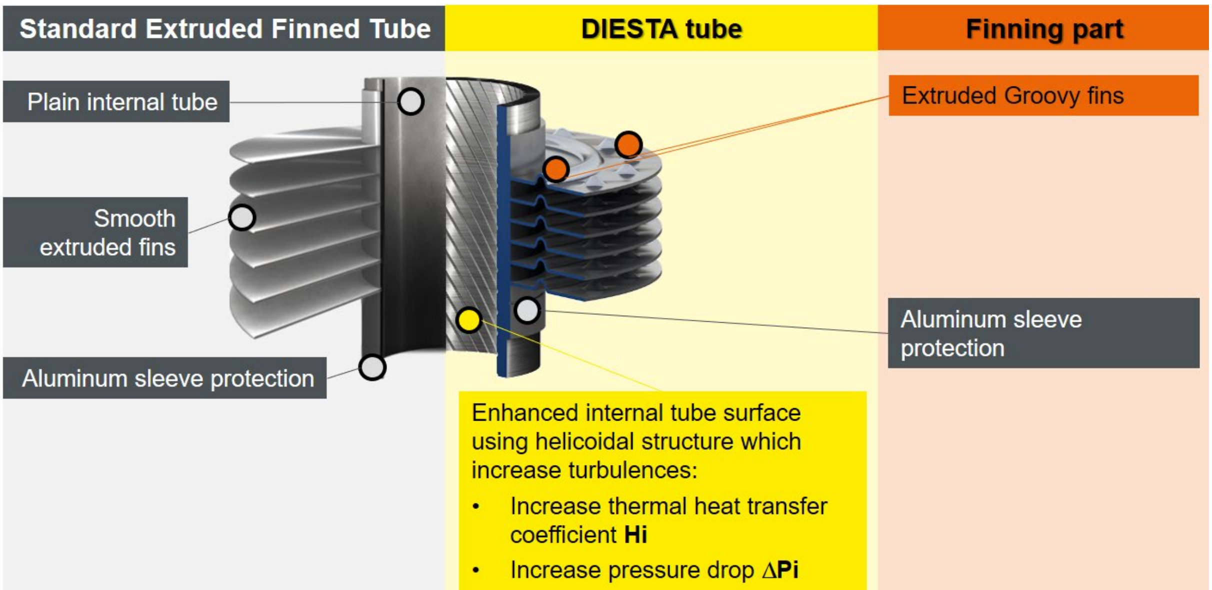

Figure 2: External and Internal enhancement with Groovy fin and Diesta technologies.

2.2 External enhancement technology

Figure 3 compares the Extruded standard fins commonly used for AFC to Extruded groovy fins developed per Kelvion. At the same fan power (same electric consumption), the increase of the external heat transfer coefficient is up to 30%.

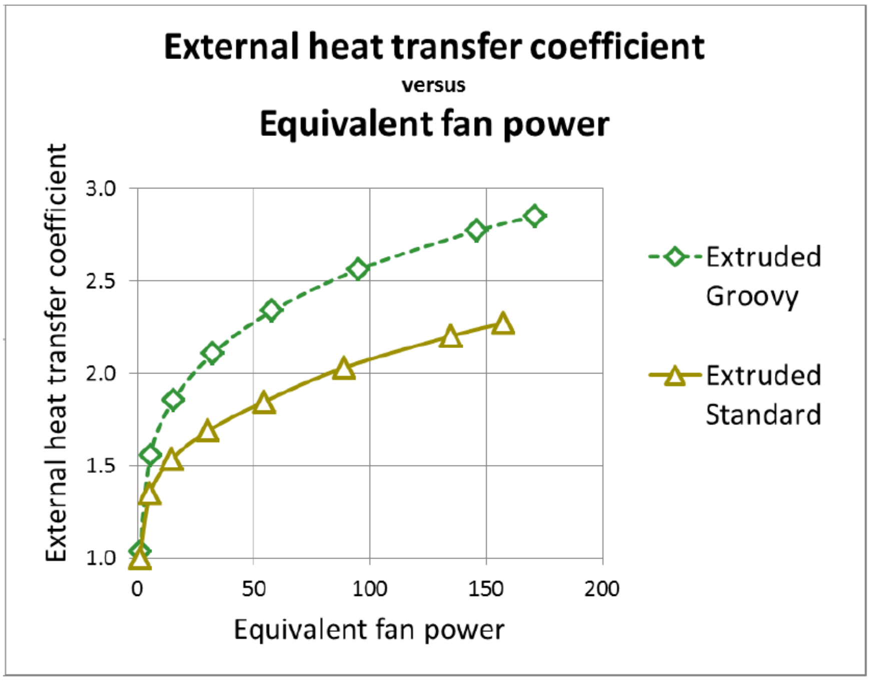

Figure 3: External enhancement with Groovy® technology compared to standard.

The technology is available and proved since 15 years. It will be used for the external finning for the SCARABEUS project.

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The goal of the task 4.1.2 is to perform the same study for internal fins of tube dedicated to the CO_2 for the project SCARABEUS.

2.3 Internal enhancement goal

The heat transfer and pressure drop in enhanced tubes were studied long time ago [1, 2, 3, 4, 5]. Nevertheless, studies dedicated to the cooling or condensing of the CO_2 are less common [6, 7, 8, 9].

The groove inside tube are used to increase the heat transfer of the heat exchanger by decreasing the internal resistance Ri. It allows increasing the turbulence inside the tube and sometimes it reduces the fouling as well.

The consequence to increase the turbulence is an increase of the pressure drop into the tube. So, the geometry of the internal fins must be a compromise between heat exchange increase and pressure drop increase.

Figure 4 shows the flow patterns differences for condensation between a smooth tube and a tube with microfins [10]. At same mass flux, the flow behavior is very different with and without inner fins.

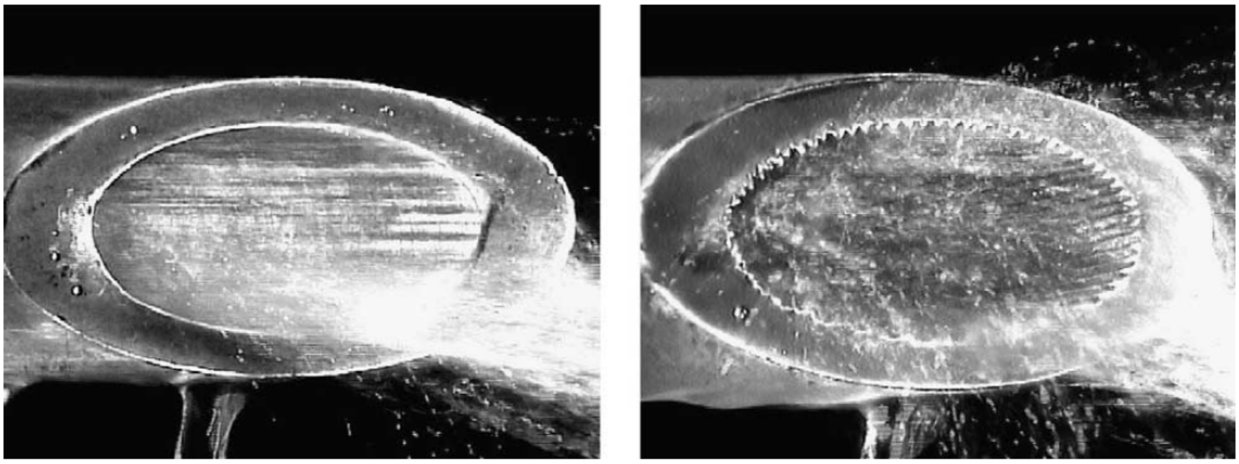

Figure 4: Comparison between flow patterns in smooth (left) and microfin (right) tube for condensation of the R134a, G=200 $kg.m^{-2}.s^{-1}$, x=0.5, Ts=40°C *[10]*.

On the left for the smooth tube, the flow is considered wavy and stratified whereas for the enhanced tube, the flow is annular.

The purpose of the literature investigation is to define the inner groove geometries for the cooling and condensing application. However, some constraints are necessary to be taken

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into account, for example the geometries of the fins and the process to manufacture the mandrel.

The literature has defined several internal enhancements (Figure 5).
Herringbone fins (a), Helical fins (b), Microstructure (c) are the one which are the most employed for the CO_2 application.

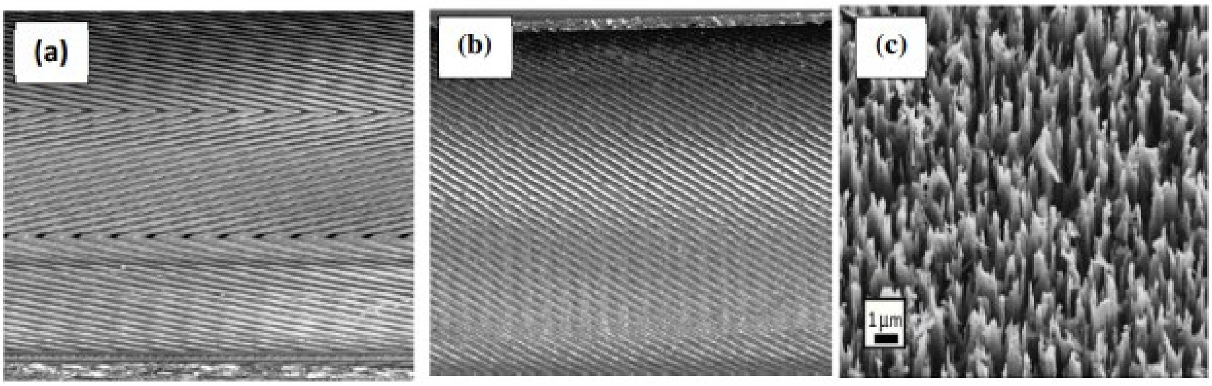

Figure 5: Internal enhancements to increase the heat transfer a-b *[11]* c: *[12]*.

The herringbone fins have a 150% greater heat transfer than comparative helical fins but also have 50 to 70% greater pressure drop [11]. Generally, the pressure drop is an important factor for industrial and an increase of 50% is not acceptable. Therefore, the DIESTA technology has been developed with helical fins.

The inner groove geometry depends on four parameters indicated by the Figure 6:

- Fin number n ;
- Fin heigh h ;
- Fin thickness e ;
- Fin helix angle α.

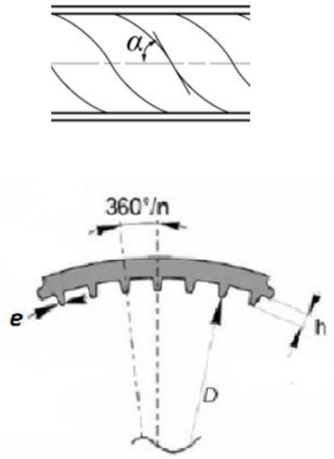

Figure 6: Parameters determining the geometry of inner fin (from *[13]*).

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Figure 7 and Figure 8 shows the helical fin structure for condensation and cooling of fluid. On Figure 8, the stripes are clearly visible.

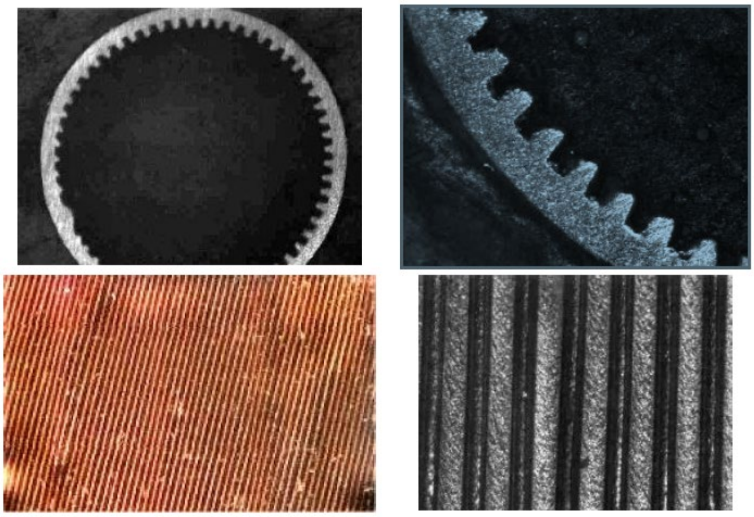

Figure 7: Helical fin structure for the condensation of CO_2 *[8]*.

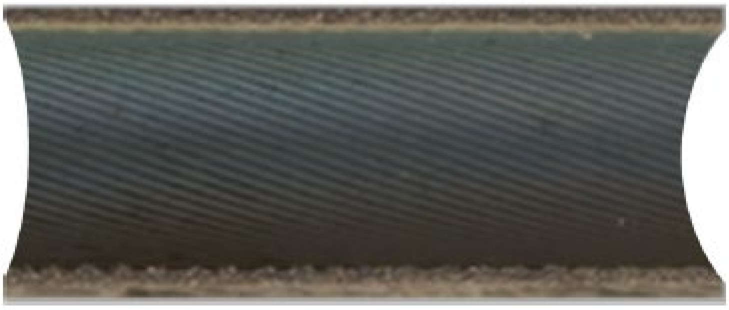

Figure 8: Helical fin structure for the cooling of R134a *[14]*.

Table 1 and Table 2 summarize the characteristics of fins geometry, the tube length and the fluid in literature respectively for several fluids and dedicated to the CO_2. The heat transfer and pressure drop increase between smooth tube and enhanced tube are also indicated.

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Table 1: Characteristics and results for condensation of several fluids

	Li et al., 2017	Biancon Copetti et al., 2004	Brognaux et al., 1996	Miyara et al., 2000
Tube inside diameter (mm)	5,89 – 7,56	8,95	14,57	0,25
Tube thickness (mm)	0,22	0,29	0,65	0,3
Tube length (mm)	2000	1090	2660	4000
Fin number n	44 - 60	60	78	50
Fin height h (mm)	0,17 – 0,23	0,2	0,35	0,21
Fin helix angle α (°)	18 - 28	18	17,5 - 27	41
Fluid	R134A	Water	Water	R410A
Hi increase (%)	537	90	95	20
DP increase (%)	N.A.	80	80	N.A.

Table 2: Characteristics and results for condensation of CO_2

	Son et al., 2012	Kim et al., 2009	Kim et al., 2009	Zilly et al., 2003	Koyama et al., 2008
Tube inside diameter (mm)	4,6	3,48	3,74	6,32	5,67
Tube thickness (mm)	0,2	0,76			0,6
Tube length (mm)	2400	1000	250	150	1376
Fin number n	55	57	57	54	50
Fin height h (mm)	0,2	0,22	0,22	0,18	0,23
Fin helix angle α (°)	40	6	6	14	3
Hi increase (%)	48	22	80	80	15
DP increase (%)	23	N.A.	N.A.	N.A.	N.A.

Generally, the fin thickness is not indicated in literature.

The number of fins varied from 44 to 78 for refrigerant and water and dedicated to the condensation of CO_2 the number is around 55 fins.

The fin height varied from 0,17 to 0,35 and for CO_2 condensation the mean is 0,21 mm.

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The fin helix angle varied from 3 to 41° and is lower than 14° for condensation of CO_2 except in one publication.

Regarding the 3 parameters proposed by literature, it is difficult to observe a preponderance of one parameter versus another. For almost the same number of fins and almost the same fin height study by Son et al. and Kim et al., the heat transfer coefficient increases from 22 to 48%. The only difference is the fin helix angle: 40° for Son et al. and 6° for Kim et al., According to these papers, the helix angle should have an impact on the heat transfer. Nevertheless, if we compare the results proposed by Kim et al., for a same helix angle of 6° the heat transfer increase from 22 to 80%. The difference is the inside diameter of the tube.

According our feedback, the parameters involved should be in the range reported in Table 3.

Table 3: Range or parameters of fins according to the fluid phase.

	Gas cooling	Condensation
Fin number n	$10 < n < 80$	$10 < n < 80$
Fin height h	$0.1 < h < 3.5$	$0.2 < h < 1$
Fin thickness e	$0.08 < e < 1.6$	$0.05 < e < 0.4$
Fin helix angle α	$\alpha < 35°$	$\alpha < 40°$

Regarding the pressure drop, there Are only three data so it is difficult to perform a detailed comparison.

The main difference with the Diesta technology developped by Kelvion is the outside diameter of the tube. Diesta is developed with 1" and 1"1/4 (25.4 mm to 31.75 mm) instead in literature the maximum diameter is 14.57mm. With such small diameter, the pressure drop in AFC should be too high.

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3 Design with HTRI

3.1 HTRI Presentation

Heat Transfer Research, Inc® (HTRI) is a commercial software for heat transfer equipment. It is used by operating companies, engineering contractors, exchanger fabricators and related industries.

It allows to design Air coolers, shell & tube, plate and frame, hairpin, jacketed pipe exchangers.

3.2 Best geometries for the inner groove

There are 4 factors influencing the heat transfer and pressure drop coefficients. In the present report, only the number of fins and its impact on the heat transfer and the pressure drop will be illustrated.

a) Condensing

Figure 9 describes the tube side film coefficient depending of the vapor quality. The tube side film coefficient is related to the heat transfer.

First, when the vapor fraction is high, the number of fins has a great impact on the heat transfer. Without fins and between 0,4 to 0,9 of vapor fraction, the heat transfer is around 12700 $W.m^{-2}K^{-1}$ and with 80 fins, the heat transfer is around 20000 $W.m^{-2}K^{-1}$. We have an improvement of almost 60%. For vapor fraction lower than 0.4, the heat transfer drop to lower than 40%.

Second, when the number of fins is higher than 70, the impact of the number of fins decrease. Therefore, it is not advantageous to add more fins. The number has an impact on the cost and the strength on the tube.

Regarding the pressure drop the statement is the same (Figure 10). The more the fins are added, the more the pressure drop increase. Nonetheless, the pressure drop is an issue has it decrease the global performance of the system.

A compromise is necessary between the heat transfer and the pressure drop to define the number of fins. It is the same for the other parameters (height, thickness and angle).

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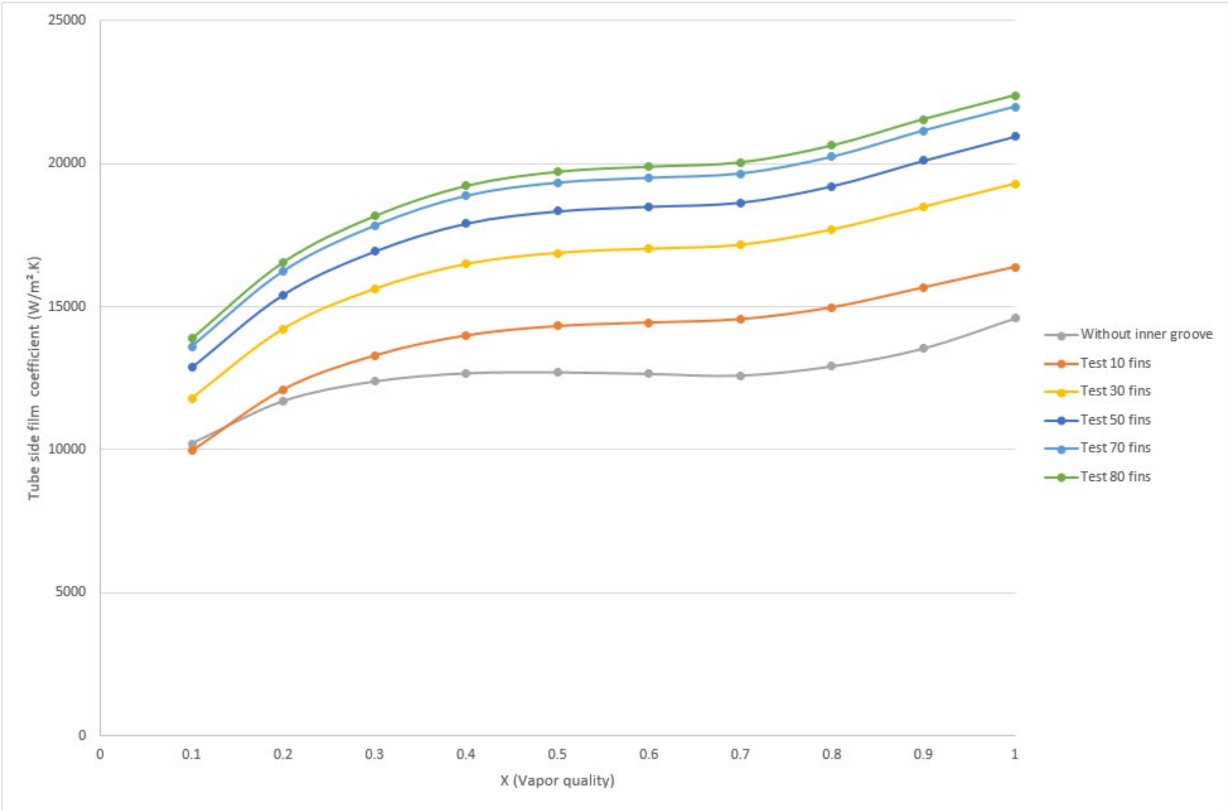

Figure 9: Tube side film coefficient according to vapor quality for CO_2 condensation.

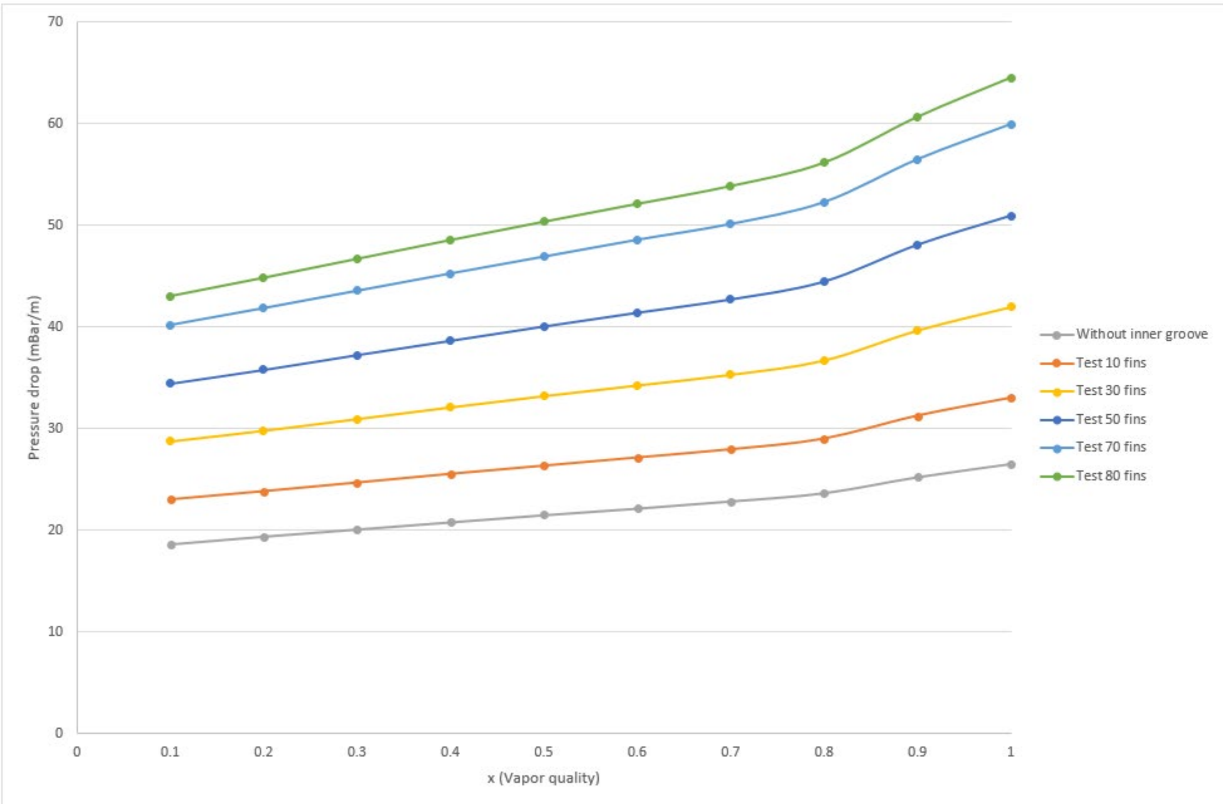

Figure 10: Pressure drop according to vapor quality for CO_2 condensation.

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Several designs have been performed varying one parameter in the range indicated in the Table 3. Figure 9 and Figure 10 show one design varying the number of fins from 0 to 80. The fixed parameters in this case are:

- Fin height h = 0.15 mm
- Fin thickness e = 0.09 mm
- Fin helix angle α = 35°

Based on all the results, the geometries of the fin have been developed. One dedicated to the CO_2 condensing (so called DIESTA CO_2 SC1) and the other to the CO_2 cooling (so called DIESTA CO_2 SC2).

The optimized geometries are not indicated in the report for confidential issue.

In the literature, the tests are performed with low diameter tubes and the correlation of enhanced tube are developed accordingly. Due to this small diameter, some doubt can be raised on the validity of the calculation with HTRI software for enhanced tube with diameter higher than 1".

For this reason, tests in real condition are necessary and this is the topic of the following sections.

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Design, Manufacturing & test of tubes sections

1 Design

The test section is designed as a tube in tube heat exchanger with the CO_2 inside the tube and the water flowing in the annulus. Figure 11 represents the scheme of the tube with the location of sensors for wall temperature, CO_2 temperature and water temperature.

The material of the test tube is carbon steel SA-179 for smooth tube and SA-334GR6 for the two enhanced tubes.

The test tube is connected to the test rig by flanges designed for 120 barg. The tube length is 1000 mm with an inlet section of 750 mm for the flow establishment and followed by an outlet section of 350 mm. The total length of the test tube is 2000 mm. The details of the design of the test section are described in Figure 13. The temperature of the CO_2 is measured at the inlet and the outlet of the test section. The differential pressure between the inlet and the outlet is also measured.

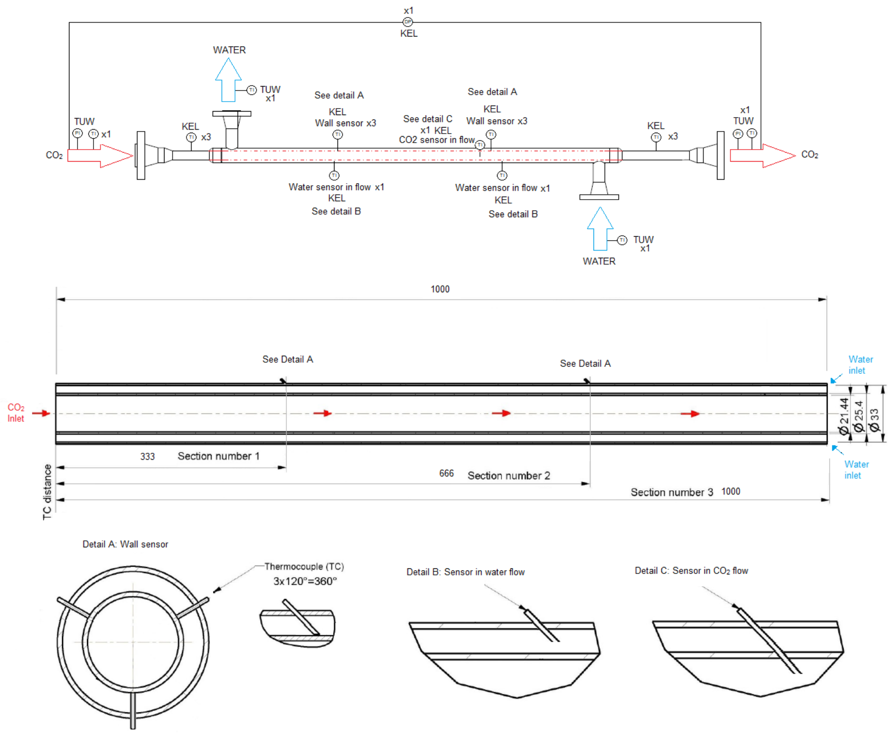

Figure 11: Schematic representation of the design of the test section.

The local wall temperature is monitored by Pt100 miniature sensors with an outer diameter 0.8mm and 1,5mm welded to the wall.

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Table 4: Main technical data of the measurement sensors of the test section.

Measured value	Position	Principle	Manufacturer	Type	Range	Accuracy
T_{wall}	Test tube	Thermocouple	SAWI	SW154-1.0x30/0.8-300-1PH4-S-V2-3.0-TED-G	-75°C to 350°C	± (0,15+0,002 * t)
$T_{flow\_of\_CO2}$	Test tube	Pt100 miniature	TC	17-1-1,5-4-300-R100-1/3-CE2LA-3 M RT48	-75°C to 350°C	± (0,1+0,0017 * t)
T_{water}	Test tube	Pt100 miniature	TC	17-1-1,5-4-300-R100-1/3-CE2LA-3 M RT48	-75°C to 350°C	± (0,1+0,0017 * t)
Δp	Inlet and outlet test section	Piezoresistive	Endress & Hauser	PMD55-EA10/125	0 to 500 mbar	± 0.055%

The annulus of the test section is connected to the water cooling system. The temperature is controlled at the inlet and the outlet of the test section.

The total heat transferred in the measuring section of the test tube is calculated by the energy balance with the assumption of no heat losses to the environment. Therefore, the entire test section was insulated with mineral wood (Insulfrax).

The test section shows several measurement points determined by thermocouple (TC) and Pt100 sensors. Each of these sections consists of three TC sensors arranged circumferential as shown in the cross view (Figure 11). The TC sensors are mounted from the outside of the shell with a single-passage watertight feedthrough and gasket. Totally, there are 12 TC sensors on the test section plus 4 sensors at the inlet and outlet to monitor the temperature of the whole test section (including 3 sensors on the Diesta tube wall).

The water and CO_2 temperatures are monitored with Pt100 sensor located into the annulus for the water cooling and directly into the tube for the CO_2.

Finally, a piezoresistive sensor allow to know the pressure drop of the whole test section.

2 Manufacturing

Figure 12 and Figure 13 illustrate the final design of the test section. The first one is a 3D view of the test section and the second one shows its characteristics (material, dimension).

The test tube are manufactured with respect to the PED standard and ASME code.

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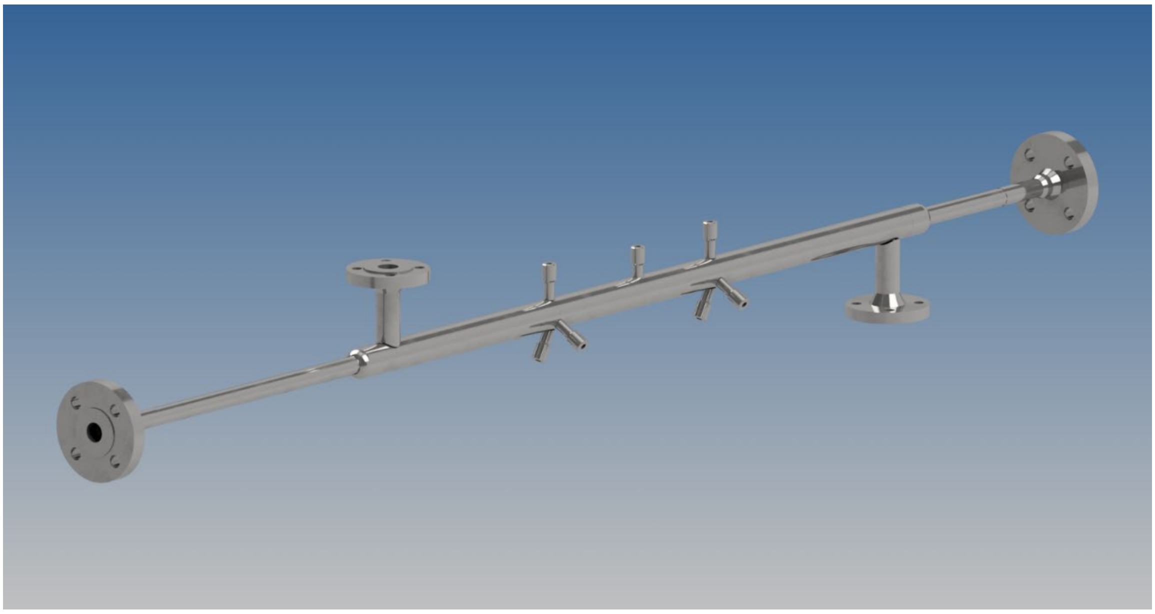
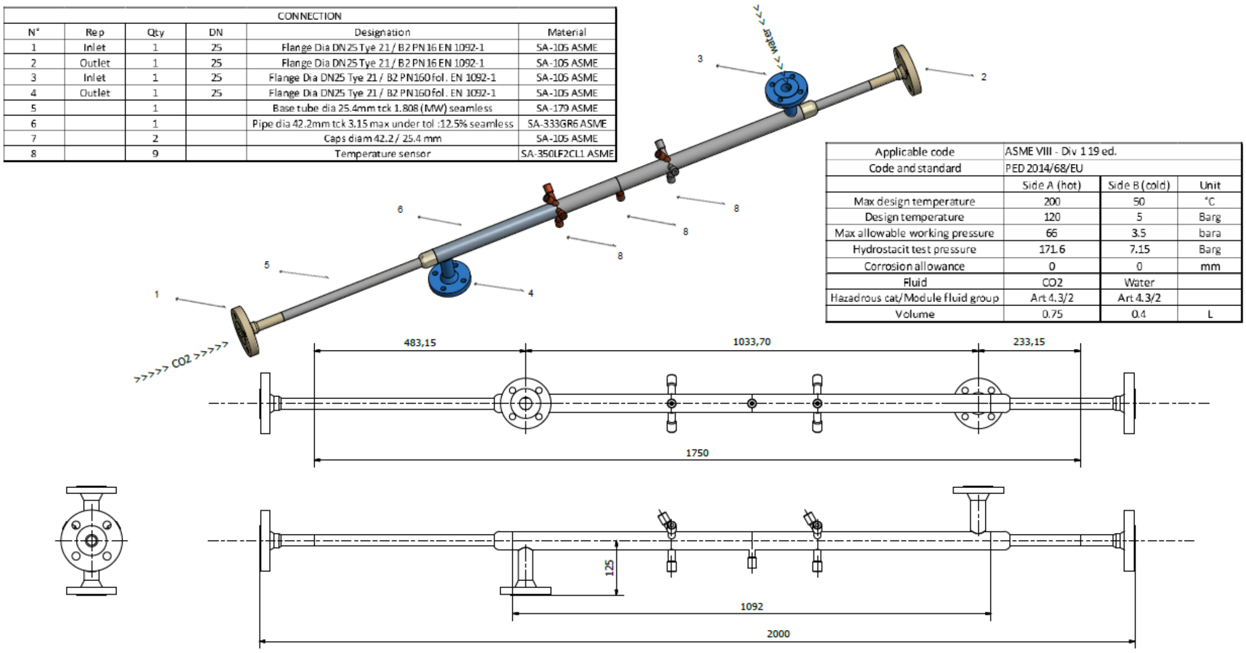


Figure 12: 3D view of the test section for SCARABEUS project.



CONNECTION					
N°	Rep	Qty	DN	Designation	Material
1	Inlet	1	25	Flange Dia DN25 Tye 21 / B2 PN16 EN 1092-1	SA-105 ASME
2	Outlet	1	25	Flange Dia DN25 Tye 21 / B2 PN16 EN 1092-1	SA-105 ASME
3	Inlet	1	25	Flange Dia DN25 Tye 21 / B2 PN160 fol. EN 1092-1	SA-105 ASME
4	Outlet	1	25	Flange Dia DN25 Tye 21 / B2 PN160 fol. EN 1092-1	SA-105 ASME
5		1		Base tube dia 25.4mm tck 1.808 (MW) seamless	SA-179 ASME
6		1		Pipe dia 42.2mm tck 3.15 max under tol :12.5% seamless	SA-333GR6 ASME
7		2		Caps diam 42.2 / 25.4 mm	SA-105 ASME
8		9		Temperature sensor	SA-350LF2CL1 ASME

Applicable code	ASME VIII - Div 1 19 ed.		
Code and standard	PED 2014/68/EU		
	Side A (hot)	Side B (cold)	Unit
Max design temperature	200	50	°C
Design temperature	120	5	Barg
Max allowable working pressure	66	3.5	bara
Hydrostacit test pressure	171.6	7.15	Barg
Corrosion allowance	0	0	mm
Fluid	CO2	Water	
Hazadrous cat/Module fluid group	Art 4.3/2	Art 4.3/2	
Volume	0.75	0.4	L

Figure 13: Design of the test section for the smooth tube.

The test tube is separated in 3 sections. At the end of section 1 and 2, PT100 and TC sensors are inserted to measure the wall temperature of Diesta tube and the temperature of water. It allows assessing the heat balance of each section so to determine the heat coefficient along the tube.

Figure 14 shows two test tubes before they successfully passed the hydraulic test. The cable of the thermocouple into the tube are visible on this picture.

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Figure 14: Two of the three test tubes before the hydraulic test.

3 Description of the test rig

The test rig is located in Wien (Austria) at the TUW. The description of the rig was reported in the deliverable 6.1 “basic and detailed process and installation design”.

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Test and definitions of heat transfer correlations (with CO_2)

1 Pressure drop

The tube side pressure drop includes the inlet and the outlet, the measuring length and the flanges. It is indicated by the difference pressure sensor (Figure 11). The pressure drop per m length is calculated by:

$$\frac{\Delta p}{m} = \frac{\Delta p}{\Delta z}$$

With Δz=2m

2 Heat transfer

The heat transfer coefficient is calculated locally at the position where thermocouples are set up on the wall of the test tubes.

The calculation of the heat transfer coefficient differs between the single phase cooling and the condensation. Below, the two cases will be described starting from the single phase cooling mode.

For the single phase cooling (Figure 15), the local temperature of CO_2 is obtained from the water temperature that is measured by a Pt-100 in the annular gap tube and the heat transferred from the hot tested fluid to the water according to the following formulas:

$$\theta = m_{water} \times \Delta h_{water}$$
$$\theta = m_{CO_2} \times \Delta h_{CO_2}$$

with:

Δh_{water} and Δh_{CO2} are the differential enthalpy of the water and CO_2 between inlet and outlet
m_{water} and m_{CO2} are the flowrate of water and CO_2.
θ is the duty and θs are equal between water and CO_2 side.

By knowing the enthalpy difference between the inlet and the outlet, it is possible to determine the temperature of the CO_2 into the tube.

To complete the data, the wall temperature of the CO_2 is necessary to reach the heat transfer coefficient. The conduction formula is used:

$$\theta = \frac{2 \cdot \lambda \cdot \pi \cdot L}{\ln \frac{R_{ext}}{R_{int}}} (T_{wall\, water} - T_{wall\, CO_2})$$

$T_{wall\ water}$ and $T_{wall\ CO2}$ are the temperature of the Diesta tube for the water and CO_2 side.

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λ is the conductivity of the tube.
R_{ext} and R_{int} are the external and internal radius of the Diesta tube.

The calculation of the local heat transfer coefficient is then calculated according to the convection formula:

$$\theta = h_{CO_2} \times S \times (T_{wall\,CO_2} - T_{CO_2})$$

With:
h_{CO2} is heat exchange coefficient for the CO_2 side.
S is the exchange surface area.
$T_{wall\ CO2}$ is the temperature of the Diesta tube for the water and CO_2 side.
T_{CO2} is the temperature of the CO_2 into the Diesta tube.

The temperature profile during the cooling phase can be represented by the Figure 15.

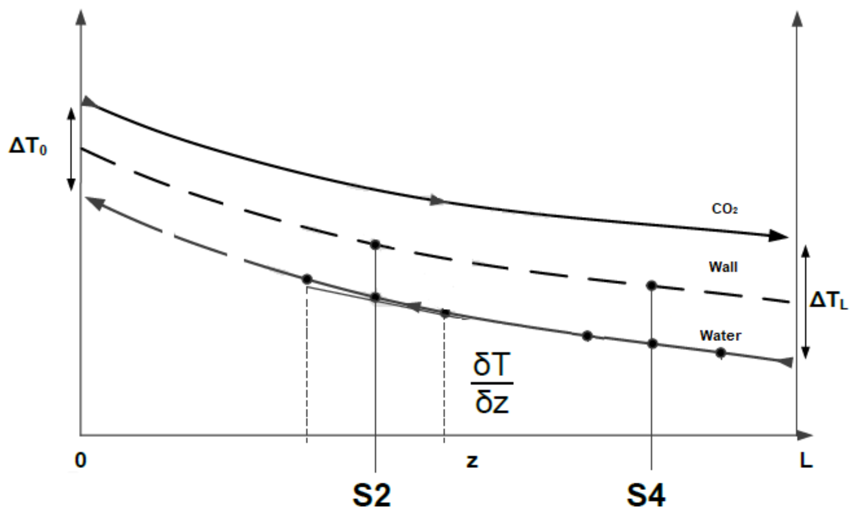

Figure 15: Temperature profile along the measuring length for single phase flow.

For the condensing phase, the CO_2 temperature is nearly constant along the tube (Figure 16). The changed in temperature results only from the pressure loss in the tube. It was checked that this temperature is constant and then not considered into the study.

The vapor quality is linked to the energy balance according to the following formula:

$$\theta = m_{CO_2} \times Lc_{CO_2} \times (x_{CO_2 out} - x_{CO_2 in})$$

with:
L_{CO2} is the latent heat of condensation
$X_{CO2\ out}$ and $X_{CO2\ in}$ are the vapor fraction at the outlet and the inlet of a section

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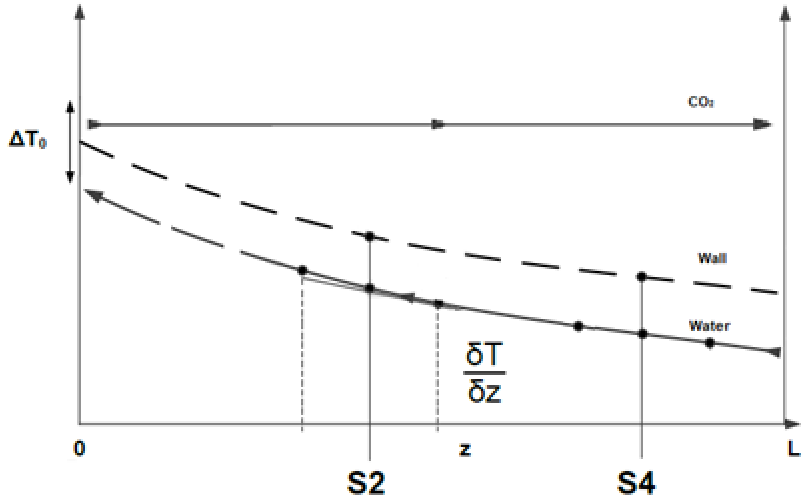

Figure 16: Temperature profile along the measuring length for condensation.

3 Result

The public report will be updated with results once there publication into scientific journal.

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Conclusions

This report has presented the design, the manufacturing and the test of tube section tailored for CO_2 test at TUW.

Firstly, the geometry of the inner fins has been studied to determine the best one according to literature, the software and the Kelvion experience. The design of the inner fin is linked to the number of fins, the fin height, the fin thickness and the helix angle. A compromise between the heat transfer and the pressure drop is used to define the best geometry of the fin dedicated to the cooling and condensation of CO_2.

Secondly, the design of the test tube was described with the location of the sensors.

The curves tendency are in accordance with the HTRi software and the literature. Nonetheless, the absolute value of the heat transfer coefficient is different than expected with HTRi. Therefore, the test performed at TUW was necessary to know the improvement during cooling and condensing phase between smooth tube and enchanced tube with inner groove.

The conclusion will be modified once results are published into scientific journal.

SCARABEUS

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