



COMPONENTS' AND MATERIALS' PERFORMANCE FOR ADVANCED SOLAR SUPERCRITICAL CO₂ POWERPLANTS

Evaluation of heat transfer and performance measurements of the HX Deliverable 5.4

WP5 Technology validation

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ABOUT THE PROJECT

COMPASSCO₂ is a 4,5-years HORIZON2020 project started on 1.11.2020. It is led by the German Aerospace Center (DLR), with eleven additional partners from seven European countries.

COMPASSCO₂ aims to integrate CSP particle systems into highly efficient s-CO₂ Brayton power cycles for electricity production. In COMPASSCO₂, the key component for such an integration, i.e. the particle/s-CO₂ heat exchanger, will be validated in a relevant environment. To reach this goal, the consortium will produce tailored particle and alloy combinations that meet the extreme operating conditions in terms of temperature, pressure, abrasion and hot oxidation/carburization of the heat exchanger tubes and the particles moving around/across them. The proposed innovative CSP s-CO₂ Brayton cycle plants will be flexible, highly efficient, economic and 100% carbon neutral large-scale electricity producers.

The research focus of COMPASSCO₂ is on three main technological improvements: development of new particles, development of new metal alloys and development of the heat exchanger section.

DISCLAIMER

This project has received funding from the European Union's Horizon 2020 Research and Innovation Action (RIA) under grant agreement No. **958418**.

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LIST OF ABBREVIATIONS

COMPASSCO ₂	Components' and Materials' Performance for Advanced Solar Supercritical CO ₂ Power Plants
CST	Concentrating Solar Thermal
EC	European Commission
EU	European Union
LMTD	Logarithmic mean temperature difference
NTU	Number of transfer units
HEX/HX	Heat exchanger
sCO ₂	Supercritical carbon dioxide

1 INTRODUCTION

The task 5.4 of work package 5 of the COMPASSCO₂ project is focused on testing and validating the performance of a particles/sCO₂ heat exchanger mock-up. The objective of this document is to present the test measurements and the performance analysis. First, the measurements and test results are shown followed by the description of the different parameters required to assess the performance of the heat exchanger including its uncertainties. Finally, the performance results of the heat exchanger are shown and discussed. Furthermore, results of the impacts test on protective materials (Task 5.2.3) are included and discussed in the Annex.

2 TEST MEASUREMENTS

The test campaign was conducted on the particles/sCO₂ heat exchanger to measure the conditions on both sides. The operation was done during several days to reach eight different steady states through the heat exchanger. Figure 1 shows the temperature measurement layout selected. Figure 2 presents the location of the temperature probes in the heat exchanger.

State						
sCO ₂	particles					sCO ₂
24; 25; 26	1	2	3	4	5	34; 35
32; 33	6	7	8	9	10	30; 31
28; 29	11	12	13	14	15	26; 27
21; 22; 23	16	17	18	19	20	21;22;23
	TP-out					

Figure 1. The temperature measurement layout based on the numbering of the temperature probes.

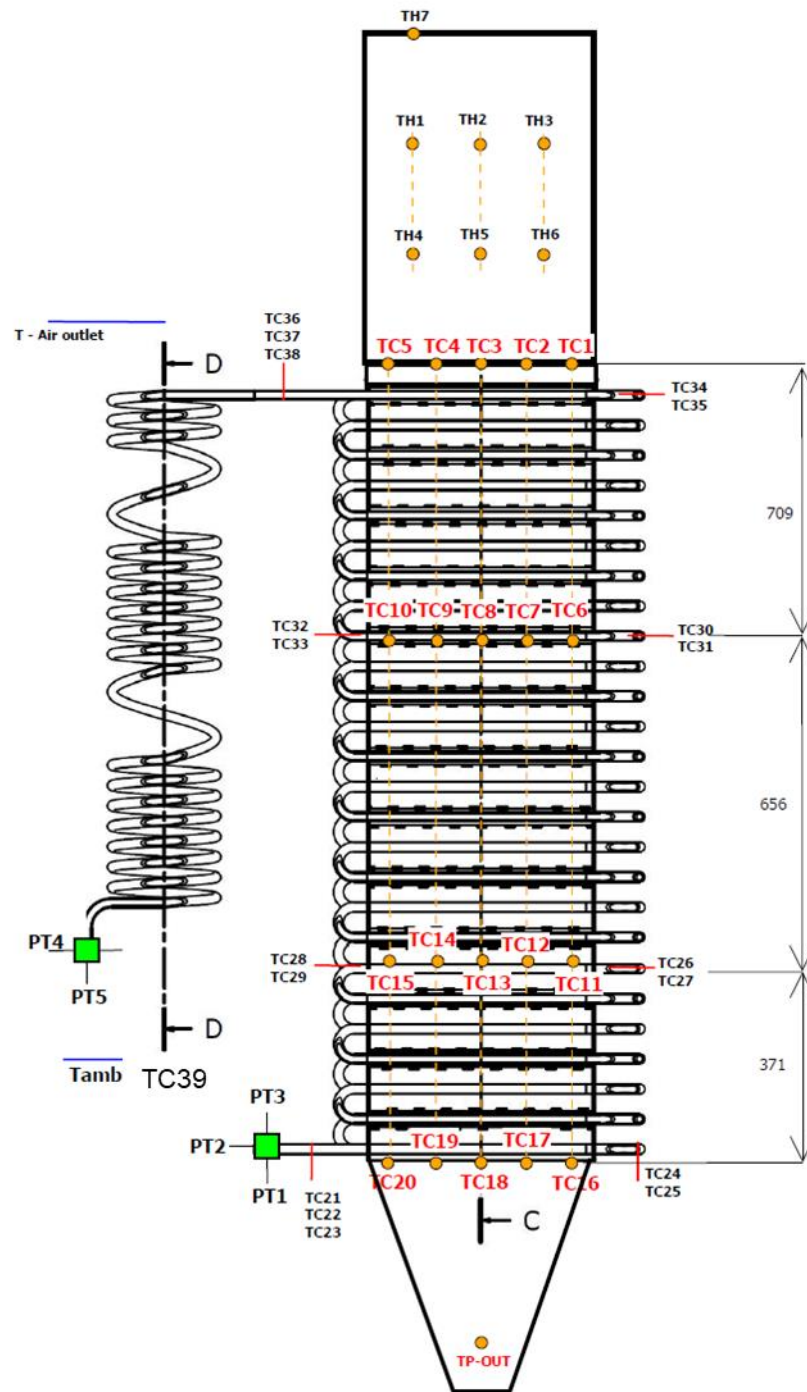


Figure 2. Temperature probes located in the heat exchanger TC1-TC20 for the particle side and TC21-TC39 for the sCO₂ – side.

The testing was conducted over two-days campaign, during which eight steady state conditions were achieved. Temperature data from these states are presented in Figure 3 and Figure 4. The red colour indicates measured values that were excluded due to wrong temperature reading and the orange colour indicates measurements with large uncertainty.

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State 1						
co2	particles					co2
405.0	299	449	415.33	276.5	434.6	399
326.5	349.2	428.225	472.74	434.3	365.8	332.8
239	300.36	344.121	357	338.8	109	243
193.8	236.326	320.4	347.6	288.99	203	200.5
345.4						
State 2						
co2	particles					co2
349.3	284.85	422.7	409.4	282.7	408.4	343.5
280.7	312.5	388.8	437.6	384.8	327.3	284
221.6	268.5	308.17	319.2	322.6	116.2	223.5
194.8	230.5	299.46	327.2	268.5	208.6	199.7
314						
State 3						
co2	particles					co2
474.9	353.5	510.9	483.57	330.1	470.9	469
409.6	423.3	495	540	500	439	415.8
330.6	380.355	420.4	435.15	411	134.6	333.3
286.7	296	385.8	416.66	366.6	265	294.6
420						
State 4						
co2	particles					co2
445.2	352.5	505	487.3	335.5	468	439
379.6	402.5	480.6	525.7	473.6	420	384
319	368.48	400.6	412.4	407.5	140	320.5
289.7	302.8	383.4	411	360.3	278.9	295.6
405						

Figure 3. The test results at the steady states 1-4 for the particles and sCO₂.

State 5						
co2	particles					co2
525.5	429.5	525.3	554.4	394	588	517
469	470.9	529	588.2	511.5	481	474.3
424.8	457.3	487.4	482.2	440.4	168	424.4
398.8	388.5	466.8	436.8	393	336	405.8
490						
State 6						
co2	particles					co2
503.4	424.5	521.4	555.5	398	581	496
452	458.2	520	577	493.8	470.1	457
420	446.2	474.9	469.1	438.4	169	419
403.4	387.3	461.5	435	393.7	336.6	409
475						
State 7						
co2	particles					co2
629.8	517.3	638.3	663.6	476	671.8	622
570.5	570.9	628.6	697.5	609.7	571.6	575
523	551.6	585.9	585.5	516.6	191	522
498.4	452.6	545.5	516.8	456	372	506
590						
State 8						
co2	particles					co2
592.3	508	617.2	630.5	456	609.4	589
550.2	553.6	604.8	663.9	585.3	565	553.5
518	541	567.6	567.9	529.3	202	515.5
500.3	456.7	541.4	523.7	471.5	394.5	507
570						

Figure 4. The test results at the steady states 5-8 for the particles and sCO₂.

Figure 5 presents the temperature distribution of the sCO₂ and particle flows over the heat exchanger width (%) at the state 7. It can be seen that some of the particle temperature measurements are not plausible. Only the second rows of each state in Figure 3 and Figure 4 present a realistic temperature distribution. The discrepancy was attributed to inconsistent thermocouple placement, which was unfortunately identified after the tests. However, the temperature profile from the second row indicated a particle flow distribution with a peak near the center and significantly lower flow near the side walls, where no temperature difference between the sCO₂ and particles is observed. This distribution was later confirmed by the oxide coloration of the heat exchanger, which was more pronounced in the middle section. This observation suggests that the available heat transfer surface was not fully utilized, and that the local heat transfer coefficient in the central region could exceed 150% of the calculated average value across the entire surface.

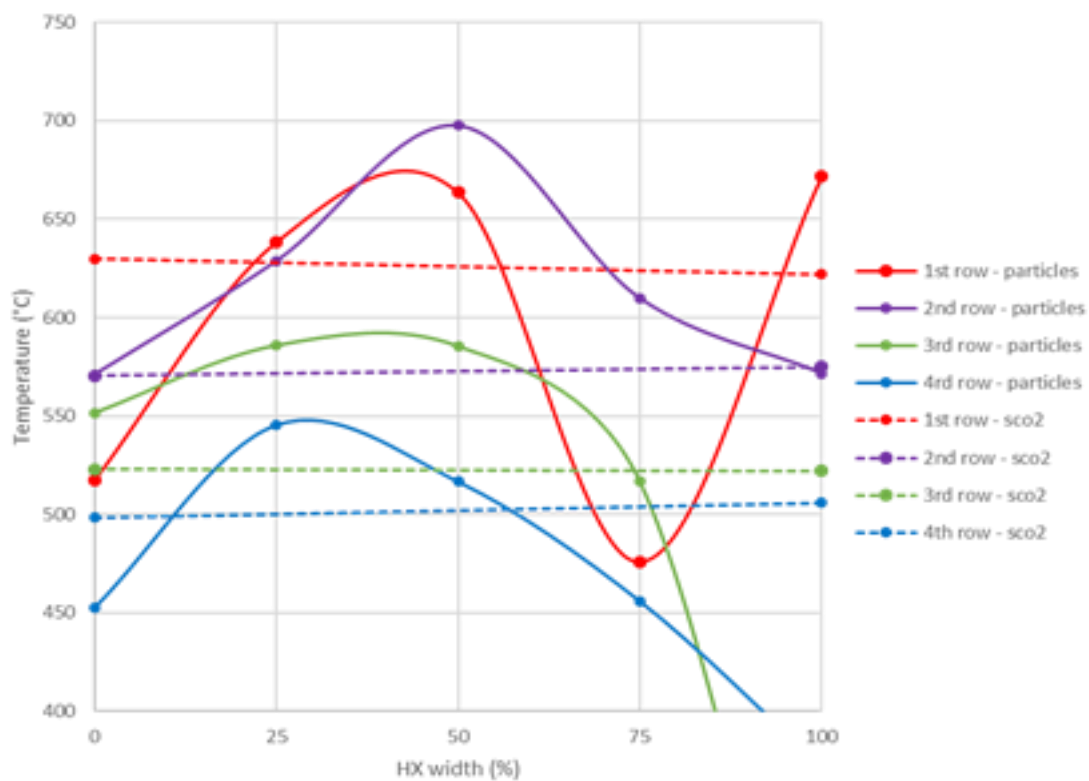


Figure 5: Temperature distribution of the sCO₂ and particle flows at the State 7.

The measured data on the sCO₂ – side is presented in Table 1 for each state including inlet and outlet temperatures ($T_{\text{co2,in}}$, $T_{\text{co2,out}}$), temperature difference (dT), mass flow ($\dot{m}$) and inlet pressure (P_{in}).

Table 1. The measured data on the sCO₂ – side

State	P_{in} (MPa)	$T_{\text{co2,in}}$ (°C)	$T_{\text{co2,out}}$ (°C)	dT (°C)	$\dot{m}_{\text{co2}}$ (kg/s)
1	15.1	194.6	407.1	212.5	0.075
2	15.1	195.4	350.6	155.2	0.111
3	15.1	288.0	477.6	189.6	0.075
4	15.1	290.7	447.1	156.4	0.111
5	15.1	400.8	528.7	127.9	0.075
6	15.5	405.0	505.7	100.7	0.111
7	15.1	501.3	634.4	133.1	0.075
8	15.1	502.6	595.4	92.8	0.111

Figure 6 presents the temperature evolution of the sCO₂ inlet and outlet during the experimental campaign, with the steady-state conditions from Table 1 clearly marked. On the first day of testing an sCO₂ outlet temperature 477°C was reached. This was followed by an overnight regime, in which the particle loop was shut down, while sCO₂ loop was maintained at constant operating parameters. On the second testing day, the sCO₂ outlet temperature peaked at 634.4°C before a failure occurred in the part of the heating section.

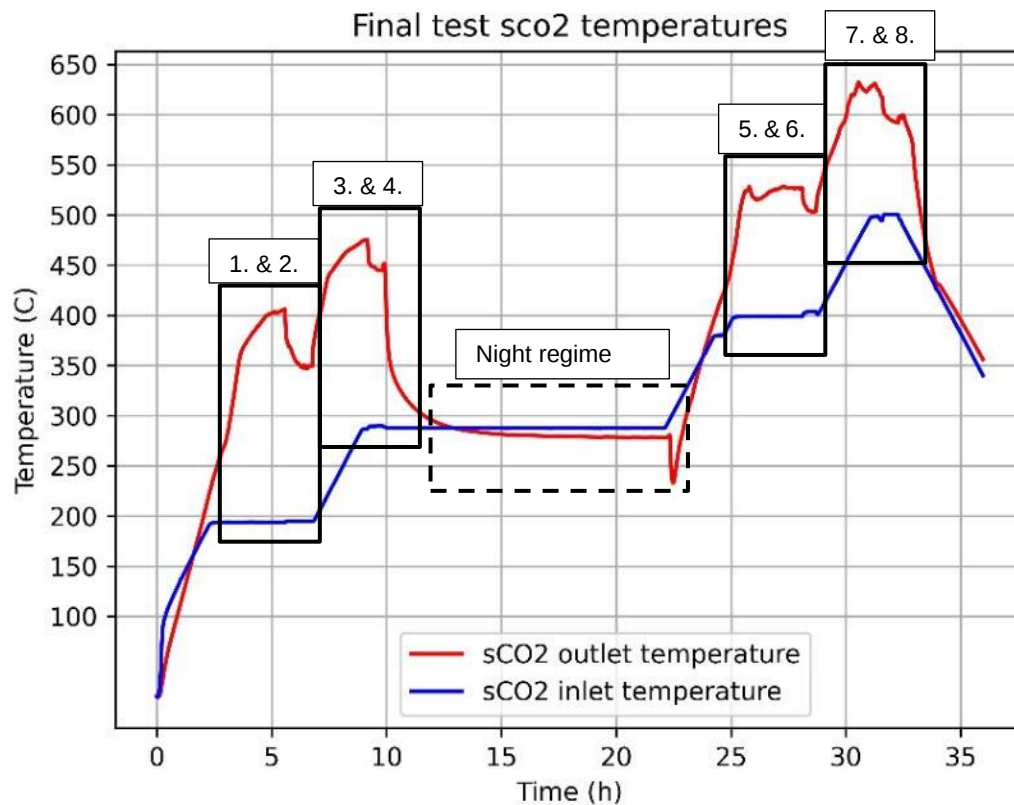


Figure 6: The steady states with the sCO₂ inlet and outlet temperatures.

To verify the particle mass flow, measurements were conducted after the experimental campaign at four temperature levels, while the settings for the screw conveyor and transport air were kept identical to those used during the test campaign. The measured values are listed in Table 2. The mean value of 0.171 kg/s was used in the performance calculations.

Table 2. The measured mass flow of the particles at different temperatures.

$T_{p, out} (^{\circ}\text{C})$	$\dot{m}_p (\text{kg/s})$
320	0.1655
455	0.1705
475	0.1788
575	0.1677

Heat losses of the heat exchanger to the ambient temperature were estimated by running the experimental without sCO₂ flow and letting the heat exchanger cool down naturally. Particle temperature measurements were collected directly after heating with an average bulk temperature of 294.7°C, followed by readings of 282.83°C after one hour (dt=3600s) and 257.66°C after approximately two hours (dt=7500s). The mass of particles contained within the heat exchanger was estimated at 123.8 kg and the outer surface area of the heat exchanger shell was 2.175 m². Based on this data, an average heat loss coefficient of 0.67 W/m²K was estimated.

3 HEAT EXCHANGER PARAMETERS AND UNCERTAINTIES

This section presents the calculation of the theoretical inlet temperature of the particles, heat losses and the performance parameters of the heat exchanger with uncertainty calculations. The results of the calculations are presented in Section 4.

3.1 PARTICLE INLET TEMPERATURE

The theoretical inlet temperature of the particles was calculated based on the heat balance of the heat exchanger due to the unreliable temperature readings at the inlet during the experimental test.

$$\dot{Q}_p = \dot{Q}_{co2} + \dot{Q}_{loss} \quad (1)$$

$$\dot{m}_p \cdot \bar{c}_{p,p} \cdot (T_{p,in} - T_{p,out}) = \dot{m}_{co2} \cdot \bar{c}_{p,co2} \cdot (T_{co2,in} - T_{co2,out}) + \dot{Q}_{loss} \quad (2)$$

The particle inlet temperature $T_{p,in}$ is solved from Eq. 2.

The heat loss coefficient was calculated for each time step of one hour as follows:

$$U_{loss} = \frac{\dot{m}_p c_{p,p} (T_{p,ave} - T_a)}{A_{shell} dt} \quad (3)$$

Finally, the heat losses are calculated as follows:

$$Q_{loss} = U_{loss} A_{shell} (T_{p,ave} - T_a) \quad (4)$$

3.2 TRANSFERRED HEAT

Supplied and captured heat of the flows (particles and sCO₂) is defined as follows:

$$\dot{Q} = \dot{m} \cdot \int_{in}^{out} c_p \cdot dT = \dot{m} \cdot (c_{p,out} \cdot T_{out} - c_{p,in} \cdot T_{in}) \quad (11)$$

Assuming a constant thermal heat capacity of both flows, the following simplification can be used:

$$\begin{aligned} \dot{Q} &= \dot{m} \cdot \bar{c}_p \cdot (T_{out} - T_{in}) \\ \text{with } \bar{c}_p &= \frac{1}{T_{out} - T_{in}} \int_{in}^{out} c_p \cdot dT \end{aligned} \quad (12)$$

The overall uncertainty of the transferred heat $u_{\dot{Q}}$ is determined by the individual uncertainties and their corresponding sensitivity coefficients (the partial derivatives) as follows:

$$u_{\dot{Q}} = \sqrt{\left(\frac{\partial \dot{Q}}{\partial \dot{m}} u_{\dot{m}}\right)^2 + \left(\frac{\partial \dot{Q}}{\partial \bar{c}_p} u_{\bar{c}_p}\right)^2 + \left(\frac{\partial \dot{Q}}{\partial T_{out}} u_{T_{out}}\right)^2 + \left(\frac{\partial \dot{Q}}{\partial T_{in}} u_{T_{in}}\right)^2} \quad (13)$$

In Eq. 4 the following partial derivatives are used:

$$\frac{\partial \dot{Q}}{\partial \dot{m}} = \bar{c}_p (T_{\text{out}} - T_{\text{in}}), \quad \frac{\text{J}}{\text{kg}} \quad (14)$$

$$\frac{\partial \dot{Q}}{\partial \bar{c}_p} = \dot{m} (T_{\text{out}} - T_{\text{in}}), \quad \frac{\text{kg}}{\text{s}} \text{K} \quad (15)$$

$$\frac{\partial \dot{Q}}{\partial T_{\text{out}}} = \dot{m} \bar{c}_p, \quad \frac{\text{W}}{\text{K}} \quad (16)$$

$$\frac{\partial \dot{Q}}{\partial T_{\text{in}}} = -\dot{m} \bar{c}_p, \quad \frac{\text{W}}{\text{K}} \quad (17)$$

3.3 LOGARITHMIC MEAN TEMPERATURE DIFFERENCE

The logarithmic mean temperature difference (LMTD) is calculated to analyze the performance of the heat exchanger. The larger the LMTD, the more heat is transferred. The LMTD determines the temperature driven for the heat transfer in the system and is calculated as follows:

$$\Delta T_m = \frac{(T_{p,\text{in}} - T_{co2,\text{out}}) - (T_{p,\text{out}} - T_{co2,\text{in}})}{\ln \left(\frac{T_{p,\text{in}} - T_{co2,\text{out}}}{T_{p,\text{out}} - T_{co2,\text{in}}} \right)} \quad (18)$$

The overall uncertainty of the LMTD $u_{\Delta T_m}$ is determined by the individual uncertainties and their corresponding sensitivity coefficients (the partial derivatives) as follows:

$$u_{\Delta T_m} = \sqrt{\left(\frac{\partial \Delta T_m}{\partial T_{p,\text{in}}} u_{T_{p,\text{in}}} \right)^2 + \left(\frac{\partial \Delta T_m}{\partial T_{p,\text{out}}} u_{T_{p,\text{out}}} \right)^2 + \left(\frac{\partial \Delta T_m}{\partial T_{co2,\text{in}}} u_{T_{co2,\text{in}}} \right)^2 + \left(\frac{\partial \Delta T_m}{\partial T_{co2,\text{out}}} u_{T_{co2,\text{out}}} \right)^2} \quad (19)$$

In Eq. 2 the following partial derivatives are used:

$$\frac{\partial \Delta T_m}{\partial T_{co2,\text{in}}} = \ln \left(\frac{T_{p,\text{in}} - T_{co2,\text{out}}}{T_{p,\text{out}} - T_{co2,\text{in}}} \right)^{-1} - \frac{(T_{p,\text{in}} - T_{co2,\text{out}}) - (T_{p,\text{out}} - T_{co2,\text{in}})}{(T_{p,\text{out}} - T_{co2,\text{in}}) \ln \left(\frac{T_{p,\text{in}} - T_{co2,\text{out}}}{T_{p,\text{out}} - T_{co2,\text{in}}} \right)^2} \ln - \quad (20)$$

$$\frac{\partial \Delta T_m}{\partial T_{co2,\text{out}}} = -\ln \left(\frac{T_{p,\text{in}} - T_{co2,\text{out}}}{T_{p,\text{out}} - T_{co2,\text{in}}} \right)^{-1} + \frac{(T_{p,\text{in}} - T_{co2,\text{out}}) - (T_{p,\text{out}} - T_{co2,\text{in}})}{(T_{p,\text{in}} - T_{co2,\text{out}}) \ln \left(\frac{T_{p,\text{in}} - T_{co2,\text{out}}}{T_{p,\text{out}} - T_{co2,\text{in}}} \right)^2} \ln - \quad (21)$$

$$\frac{\partial \Delta T_m}{\partial T_{p,in}} = \ln \left(\frac{T_{p,in} - T_{co2,out}}{T_{p,out} - T_{co2,in}} \right)^{-1} - \frac{(T_{p,in} - T_{co2,out}) - (T_{p,out} - T_{co2,in})}{(T_{p,in} - T_{co2,out}) \ln \left(\frac{T_{p,in} - T_{co2,out}}{T_{p,out} - T_{co2,in}} \right)^2} \ln - \quad (22)$$

$$\frac{\partial \Delta T_m}{\partial T_{p,out}} = -\ln \left(\frac{T_{p,in} - T_{co2,out}}{T_{p,out} - T_{co2,in}} \right)^{-1} + \frac{(T_{p,in} - T_{co2,out}) - (T_{p,out} - T_{co2,in})}{(T_{p,out} - T_{co2,in}) \ln \left(\frac{T_{p,in} - T_{co2,out}}{T_{p,out} - T_{co2,in}} \right)^2} \ln - \quad (23)$$

3.4 HEAT TRANSFER COEFFICIENTS

The overall heat transfer coefficient between the particle and sCO₂-side of the heat exchanger tubing is calculated based on the transferred heat and the LMTD. The sCO₂ flow receives thermal energy from the particle flow.

$$U = \frac{\dot{Q}}{\Delta T_m A_o} \quad (24)$$

The overall uncertainty of the overall heat transfer coefficient u_U is determined by the individual uncertainties and their corresponding sensitivity coefficients (the partial derivatives) as follows:

$$u_U = \sqrt{\left(\frac{\partial U}{\partial \dot{Q}} u_{\dot{Q}_p} \right)^2 + \left(\frac{\partial U}{\partial \Delta T_m} u_{T_m} \right)^2 + \left(\frac{\partial U}{\partial A_o} u_{A_o} \right)^2} \quad (25)$$

$$\frac{\partial U}{\partial \dot{Q}} = \frac{1}{\Delta T_m A_o} \ln \frac{1}{K \text{ m}^2} \quad (26)$$

$$\frac{\partial U}{\partial \Delta T_m} = -\frac{\dot{Q}}{\Delta T_m^2 A_o} \ln \frac{1}{K^2 \text{ m}^2} \quad (27)$$

$$\frac{\partial U}{\partial A_o} = -\frac{\dot{Q}}{\Delta T_m A_o^2} \ln \frac{1}{K \text{ m}^4} \quad (28)$$

3.5 EFFECTIVENESS AND NUMBER OF TRANSFER UNITS

The effectiveness and number of transfer units (NTU) method defines the performance of the heat exchanger as a ratio of the transferred heat to the theoretical maximum transferrable heat in the heat exchanger. The higher NTU value indicates the better usability of the available surface for the heat transfer.

$$\epsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{\dot{Q}}{\min(\dot{C}_p, \dot{C}_a) (T_{p,\text{in}} - T_{co2,\text{in}})} \quad (29)$$

The overall uncertainty of the effectiveness u_ϵ is determined by the individual uncertainties and their corresponding sensitivity coefficients (the partial derivatives) as follows:

$$u_\epsilon = \sqrt{\left(\frac{\partial \epsilon}{\partial \dot{Q}} u_{\dot{Q}}\right)^2 + \left(\frac{\partial \epsilon}{\partial \dot{C}_{\min}} u_{\dot{C}_{\min}}\right)^2 + \left(\frac{\partial \epsilon}{\partial T_{p,\text{in}}} u_{T_{p,\text{in}}}\right)^2 + \left(\frac{\partial \epsilon}{\partial T_{co2,\text{in}}} u_{T_{co2,\text{in}}}\right)^2} \quad (30)$$

$$\frac{\partial \epsilon}{\partial \dot{Q}} = \frac{1}{\dot{C}_{\min} (T_{p,\text{in}} - T_{co2,\text{in}})} \text{ in } \frac{1}{\text{W}} \quad (31)$$

$$\frac{\partial \epsilon}{\partial \dot{C}_{\min}} = -\frac{\dot{Q}}{\dot{C}_{\min}^2 (T_{p,\text{in}} - T_{co2,\text{in}})} \text{ in } \frac{\text{kg} \cdot \text{K}}{\text{J}} \quad (32)$$

$$\frac{\partial \epsilon}{\partial T_{co2,\text{in}}} = -\frac{\dot{Q}}{\dot{C}_{\min} (T_{p,\text{in}} - T_{co2,\text{in}})^2} \text{ in } \frac{1}{\text{K}} \quad (33)$$

$$\frac{\partial \epsilon}{\partial T_{p,\text{in}}} = \frac{\dot{Q}}{\dot{C}_{\min} (T_{p,\text{in}} - T_{co2,\text{in}})^2} \text{ in } \frac{1}{\text{K}} \quad (34)$$

The NTU is calculated as follows:

$$NTU = \frac{U A_{\text{in}}}{\dot{C}_{\min}} \quad (35)$$

The overall uncertainty of the NTU u_{NTU} is determined by the individual uncertainties and their corresponding sensitivity coefficients (the partial derivatives) as follows:

$$u_{NTU} = \sqrt{\left(\frac{\partial NTU}{\partial U} u_U\right)^2 + \left(\frac{\partial NTU}{\partial A_{\text{in}}} u_{A_{\text{in}}}\right)^2 + \left(\frac{\partial NTU}{\partial \dot{C}_{\min}} u_{\dot{C}_{\min}}\right)^2} \quad (36)$$

$$\frac{\partial NTU}{\partial U} = \frac{A_{\text{in}}}{\dot{C}_{\min}} \text{ in } \frac{\text{m}^2 \text{ s K}}{\text{J}} \quad (37)$$

$$\frac{\partial NTU}{\partial A_{\text{in}}} = \frac{U}{\dot{C}_{\min}} \text{ in } \frac{1}{\text{m}^2} \quad (38)$$

$$\frac{\partial NTU}{\partial \dot{C}_{\min}} = -\frac{U A_{\text{in}}}{\dot{C}_{\min}^2} \text{ in } \frac{\text{K s}}{\text{J}} \quad (39)$$

3.6 UNCERTAINTY CALCULATION

The total measurement uncertainty considers both the equipment uncertainty and reading uncertainty as follows:

$$u = \sqrt{u_{eq}^2 + u_{rd}^2} \quad (40)$$

The first is given by the manufacturer of the measurement equipment and the second is the results of the experimental standard deviation of the mean from a number of repeated measurements. The rectangular distribution is used to apply for the manufacturer provided uncertainties. The reading uncertainty is presented as follows:

$$u_{rd} = s(V_m) = \frac{s(V)}{\sqrt{n}} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^n (V_i - V_m)^2} \quad (41)$$

In this report, the reading uncertainty is considered only in terms of temperatures due to the availability of the repeated measurements. For the other parameters, such as mass flow and heat capacity, only the equipment uncertainty was considered in the uncertainty calculations due to the lack of the statistical data to calculate the reading uncertainty.

4 PERFORMANCE ANALYSIS AND RESULTS

The theoretical inlet temperature of the particles and the performance parameters presented in Section 3 were calculated with the uncertainties for each steady states of the experimental test. The results are presented in

Table 3.

In the uncertainty calculations, the dimension accuracy of 0.0003 m was considered according to ISO 2768-mK and for the temperatures the values of 1.3°C at 200°C, 1.4°C at 500°C and 3.7°C at 200°C from the calibration list were used to estimate uncertainty at each measured temperature. The uncertainty of the mass-flow measurements was given to be ±10% for both flows. The uncertainty of ±1% was considered for the heat capacity measurements based on REFPROP.

Table 3. Calculated performance results of the heat exchanger.

State	$T_{p,in}$ (°C)	$\dot{Q}_p$ (kW)	$\dot{Q}_{co2}$ (kW)	$\dot{Q}_{loss}$ (kW)	LMTD (°C)	U (W/m ² K)	ε (-)	NTU (-)
1	473.8	20.05 ± 1.20	19.31 ± 1.13	0.57	103.1 ± 0.88	126.3 ± 6.9	0.71 ± 0.056	1.91± 0.15
2	455.1	22.11 ± 1.30	20.92 ± 1.22	0.53	111.4 ± 0.78	126.6 ± 6.9	0.56 ± 0.045	1.31 ± 0.10
3	530.5	18.40 ± 1.07	17.13 ± 1.00	0.66	86.5 ± 0.98	133.5 ± 7.4	0.78 ± 0.064	2.19 ± 0.18
4	539.6	22.14 ± 1.29	20.88 ± 1.22	0.66	103.0 ± 0.85	136.6 ± 7.4	0.63 ± 0.052	1.52± 0.12
5	564.9	13.08 ± 0.75	11.66 ± 0.69	0.74	58.8 ± 1.05	133.7 ± 7.9	0.79 ± 0.066	2.21± 0.18
6	562.0	14.97 ± 0.86	13.57 ± 0.8	0.73	62.9 ± 0.89	145.5 ± 8.3	0.65 ± 0.054	1.62± 0.13
7	667.7	14.06 ± 0.82	12.30 ± 0.73	0.89	56.5 ± 1.33	146.7 ± 9.2	0.81 ± 0.068	2.39± 0.20
8	650.0	14.35 ± 0.83	12.67 ± 0.76	0.86	60.8 ± 1.07	140.5± 8.4	0.64 ± 0.054	1.54± 0.13

Based on the calculations, the theoretical inlet temperature of the particles was derived for each steady state starting from 473.8°C and reaching the maximum of 667.7°C at the 7th state. The maximum transferred heat of 20.92 kW to the sCO₂ – flow was reached on the state 2 with the sCO₂ inlet and outlet temperatures of 195.4°C and 350.6°C, respectively. This was followed also by the highest LMTD of 111.4°C. The heat losses were significantly lower than transferred heat but increased slightly linearly with the particle inlet temperature. The overall heat transfer coefficient ranged from 126.3 to 146.7 W/m²K across the different steady states, which is considered relatively high and exceeded the initial estimates.

The overall heat transfer coefficient was plotted as function of sCO₂ outlet temperature, as shown in Figure 7. A linear trend was fitted to the data to predict the thermal performance at higher temperatures. Although the trend shows a moderate increase with temperature, it suggests that an overall heat transfer coefficient of 150 W/m²K could be reached at a sCO₂ outlet temperature of 700°C.

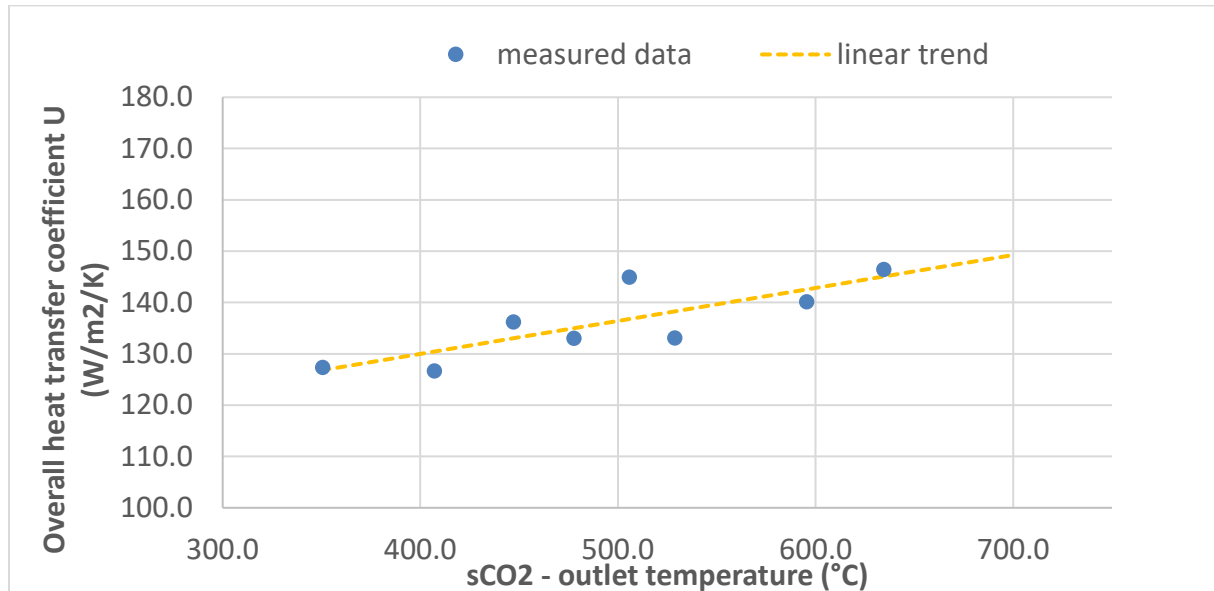


Figure 7: Relation between the overall heat transfer coefficient and measured outlet temperature of sCO₂.

5 CONCLUSIONS

The evaluation of heat transfer and performance measurements of the particle – sCO₂ heat exchanger mock-up was presented in this report. First, the measured results of the experimental testing of the heat exchanger were presented with the set-up layout. Next, the calculations of the performance parameters were presented followed by the results with uncertainties and conclusion.

The results show a good thermal performance of the heat exchanger. The maximum sCO₂ outlet temperature of 634.4°C was reached with the particle theoretical inlet temperature of 667.7°C at the state 7. The maximum U-value of 146.4 W/m²K was reached at the same state.

The target sCO₂ temperature of 700°C was not reached due to a heater section failure. However, based on the extrapolated trend, an overall heat transfer coefficient of approximately 150 W/m²K is expected to be achievable at the target temperature. Moreover, addressing the non-uniform particle flow distribution could potentially lead to a significant increase in this value by enabling more effective use of the heat transfer surface. It is estimated that a value of around 200 W/m²K can be reached for an optimized set-up.

6 ANNEX

6.1 IMPACT TEST OF HOT PARTICLES ON IMPACT ZONES

To investigate material wear caused by particle impacts at high temperatures (>600°C) and velocities approaching speeds that can occur at the outlet of a centrifugal solar receiver an impact test was conducted.

The impact plate was installed in the particle/air separator section, positioned at a 20° angle relative to the outflow nozzle, where the air-particle mixture flows, as illustrated in Figure 8. The impact plate was manufactured from Inconel 625 and designed to hold a material sample (shown in Figure 9), with an exposed area 30x50 mm. A thermocouple was attached to the back of the sample to monitor its temperature during testing.

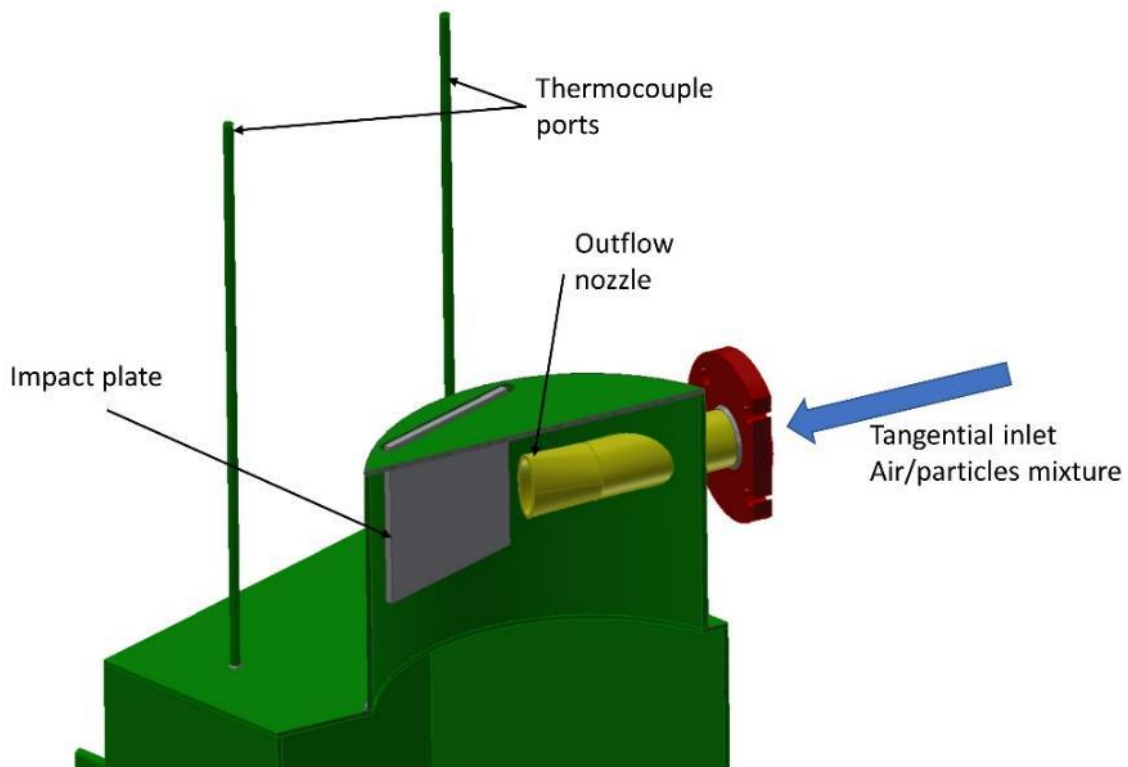


Figure 8: Impact test setup – Impact plate positioning.

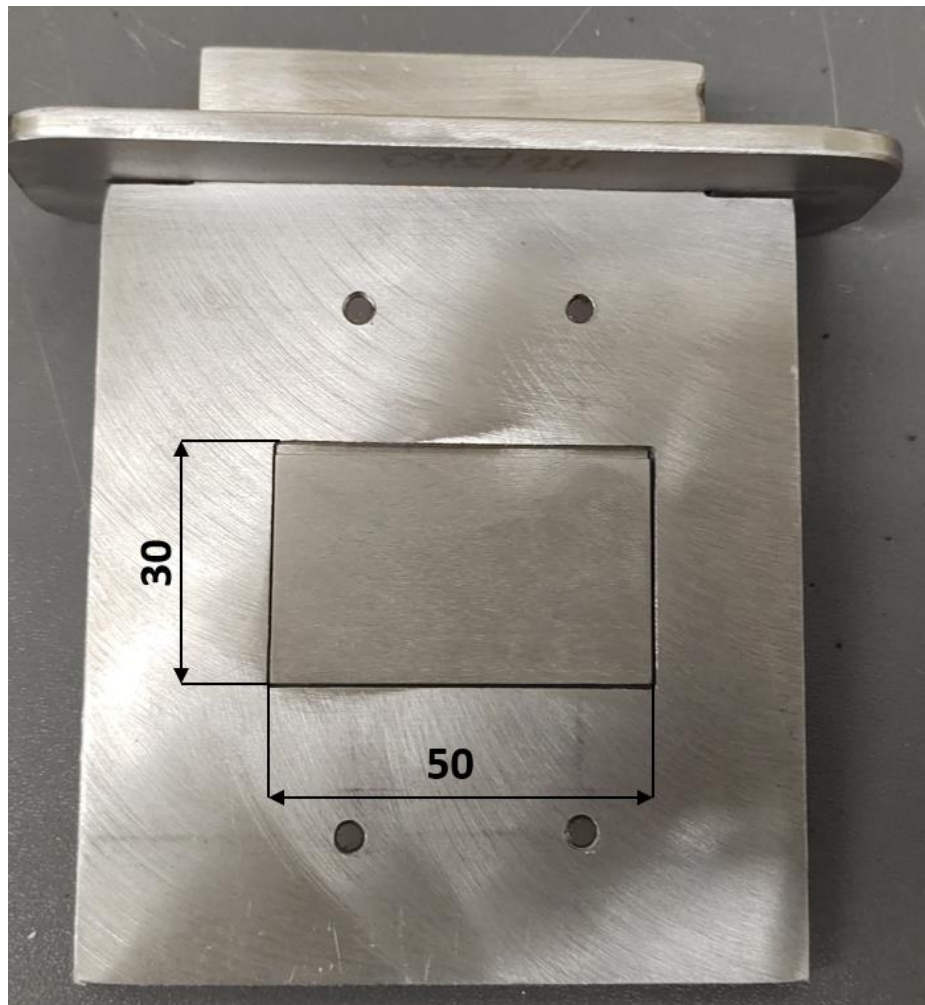


Figure 9: Impact plate - sample holder.

6.1.1 Impact test - material selection, boundary conditions and results

As the primary focus was to evaluate the ceramic materials, alumina oxide and silica carbide were selected as promising candidates for testing. In addition, plasma-coated samples, one with alumina oxide 96% purity and another with a mixture of alumina oxide and TiO₂ in an 87/13% ratio were also tested. Stainless steel AISI 316 was used as a reference material, as it is a commonly used construction alloy and was representative of the surrounding components.

The impact velocity could not be measured directly, but it was estimated using CFD (computational fluid dynamics) simulation. In these simulations, total mass-flows of both air and particles were known as well as the temperatures. The CFD model employed an Eulerian multiphase approach with a steady-state fluid phase and Dense Discrete Phase model (DDPM) featuring unsteady particle tracking. The computational domain included the initial section of the particle feed track and the air-particle separator.

The resulting particle velocity field (illustrated in Figure 10), indicates an impact velocity of approximately 8m/s near the impact plate. This velocity corresponds to the constant mass-flows of air and particles maintained during the tests. The temperatures measured on the back side of the sample reached approximately 675°C.

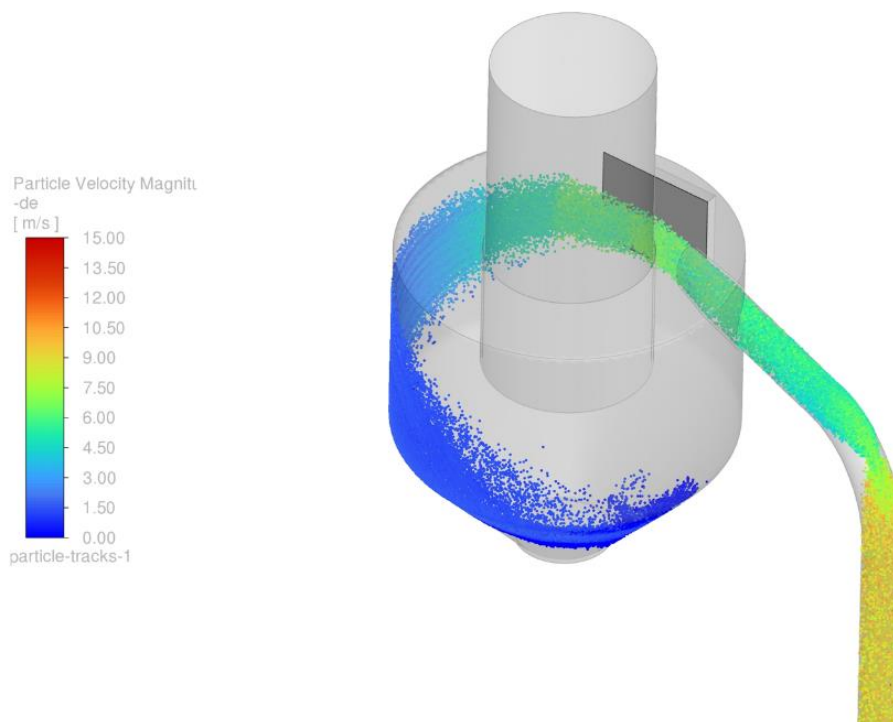


Figure 10: CFD calculation air-particles separator - velocity contours.

The exposure duration for each sample is listed in Table 4. Generally, samples were replaced at the end of each experimental campaign. It is important to note that the silica carbide sample used during the 4th and 5th campaigns broke after the exposure, during removal from the sample holder. However, testing with a new SiC sample was repeated during the 7th campaign.

Table 4: Impact tests duration and sample exposure.

Campaign	Test duration at operation param.(h)	Impact test
1	99	x
2	99	SS316
3	121	Al ₂ O ₃
4	91	Sic - (broke)
5	99	Sic - (broke)
6	156	Coating
7	171	SiC
Total	836	

Each sample's weight was measured before and after testing, and the mass loss due to abrasion was evaluated based on standardized interval of 100 hours, which corresponds to the typical exposure duration achieved by each sample.

The resulting mass loss per 100 hours is presented in Figure 11, where the performance of selected ceramic materials is compared to that of the reference stainless steel (SS2). The stainless steel experienced a mass loss of 25.74g/100h, whereas the ceramics exhibited significantly lower wear: 0.171g/100h for Al₂O₃ and just 0.039g/100h for SiC, which is several orders of magnitude lower.

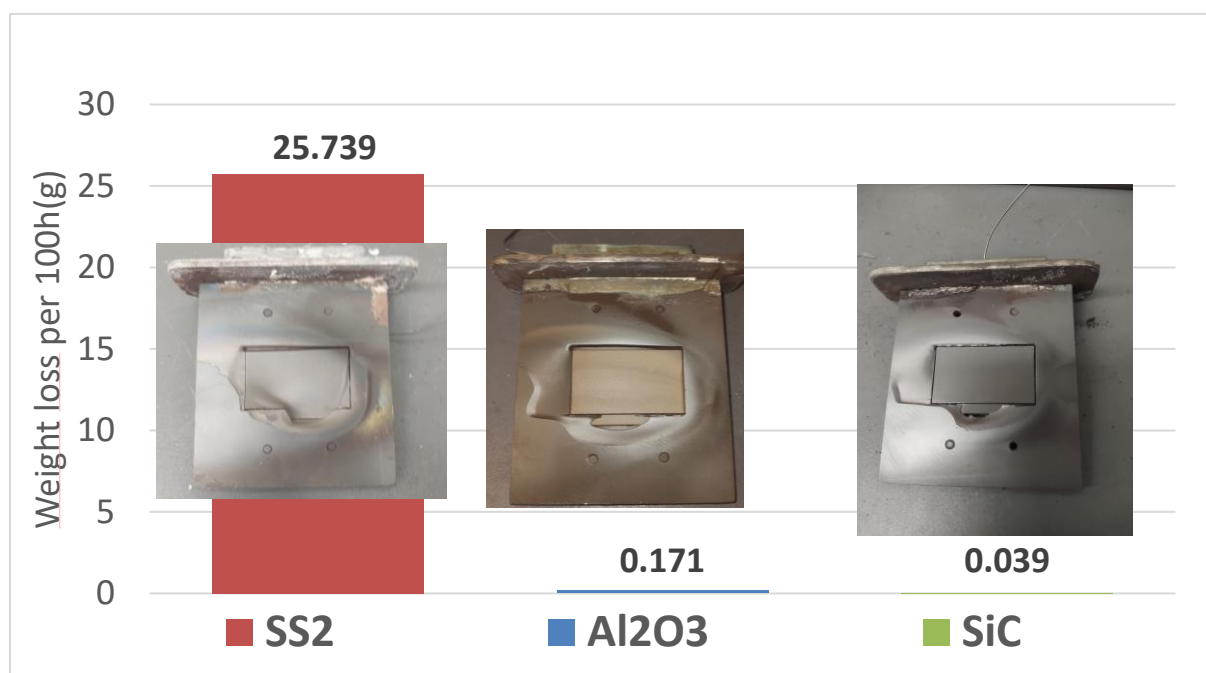


Figure 11: Comparison of the weight loss/100h for selected materials.

Since the plasma coated samples had a different topology, they could not be quantitatively compared with the other test samples and were therefore evaluated through the visual inspection. In Figure 12 and Figure 13 are shown the coatings before and after exposure. Both coatings exhibited cracking that led to spallation of the coated layer. In case of the 96% Al₂O₃ sample, the coating remained largely intact after 56 hours of exposure, but showed signs of degradation that suggest it would fail similarly to the 87% Al₂O₃ +13% TiO₂ coating, which was completely missing within the impact area after 100h test duration.

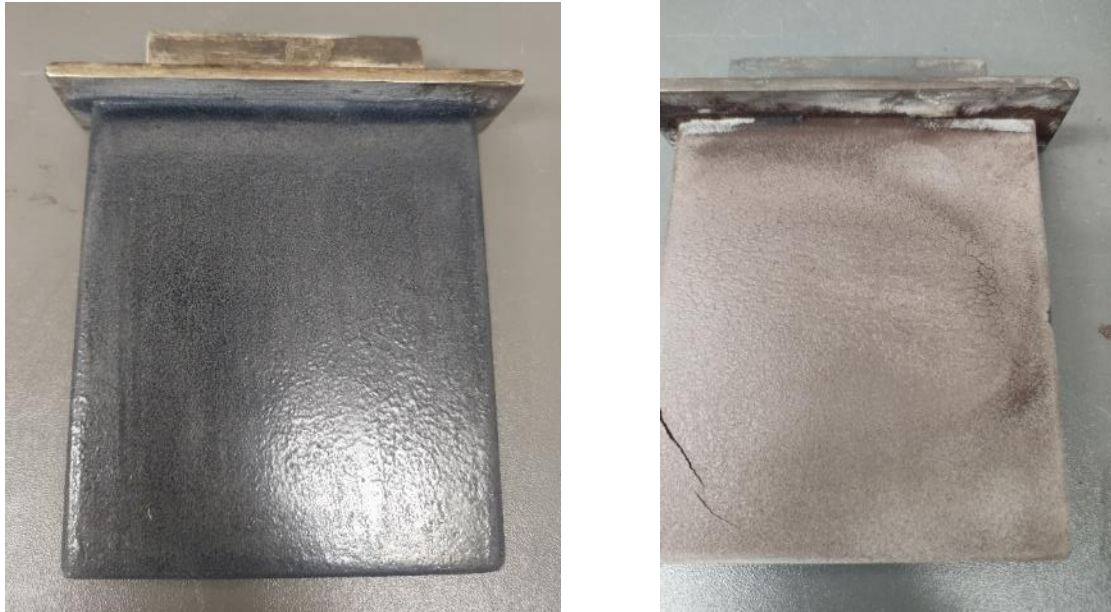


Figure 12: Plasma coated 96% Al₂O₃ sample. Before exposure (on the left), after 56h (on the right)

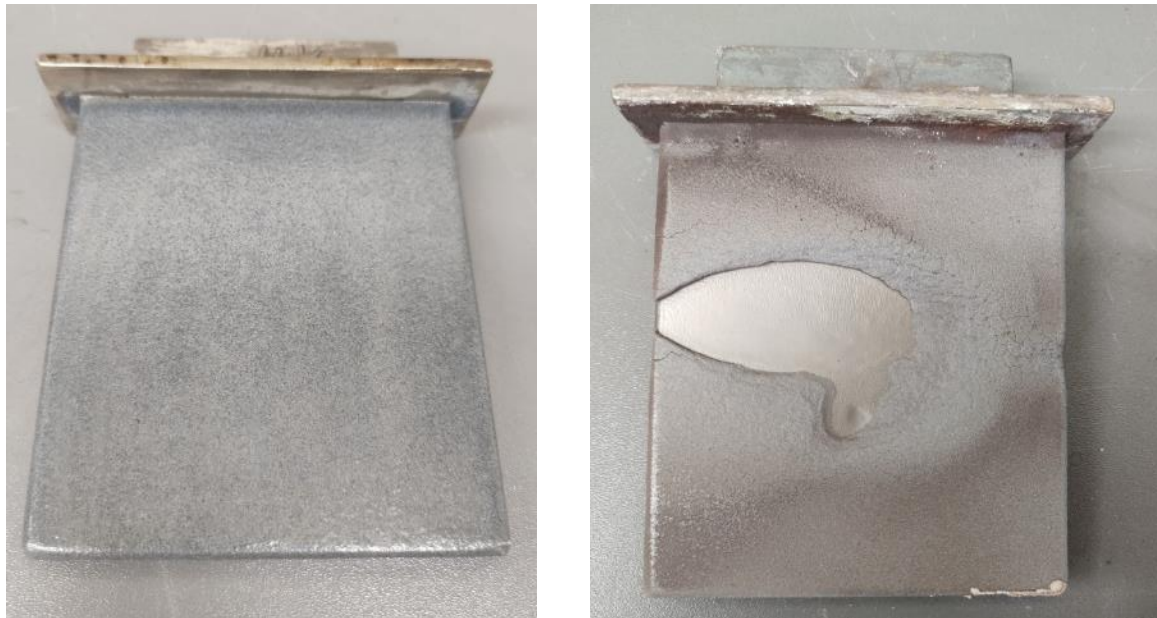


Figure 13: Plasma coated 87% Al₂O₃ + 13%TiO₂ sample. Before exposure (on the left), after 100h (on the right)

6.1.2 Impact test conclusion

In conclusion, ceramic materials have demonstrated strong potential as protective layers against particle-induced wear under conditions similar to those tested, significantly extending the service life of exposed components. Among the ceramics, silicon carbide exhibited superior performance with the lowest mass loss; however, its brittleness poses challenges for practical implementation in manufacturing protective components.

Stainless steel and nickel-based alloys, despite their relatively high hardness, proved unsuitable under these conditions without additional protective measures, offering only limited service life.

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Plasma coating technology, while generally promising and cost-effective for base material protection, did not perform well under the specific test conditions used in this study. Nonetheless, further research may improve coating adhesion and reduce spallation, making it a more viable solution in the future.