Experimental and Numerical Investigations of a 3D-printed Monolithic Channel Inconel Receiver in Hot Sodium up to 500°C

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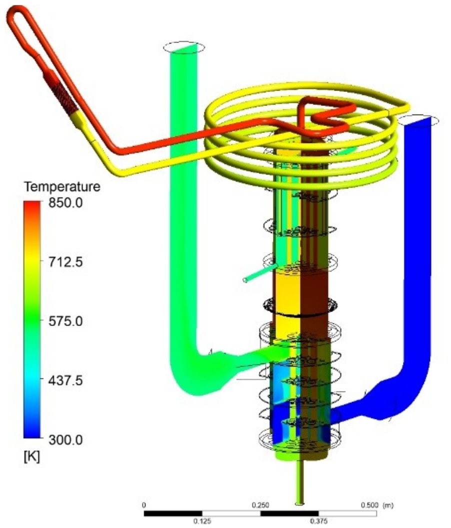

Introduction

- R&D activities at KIT-INR in the CSP field:
  - Experimental and numerical investigations of heat storage solutions (TES);
  - Experimental and numerical investigations of instrumentation (flow sensors [1]) and components (receiver [2]) in hot sodium;
  - Development and qualification of new materials for HT receivers.
- Present study (ongoing investigation) focuses on temperature measurements and test of 3D-printed monolithic channel [3] up to 500°C:
  - Gain of first operational experience in the general usage of a monolith receiver;
  - Validation of CFD code.
- SOLTEC-2 [4]: 1000 K sodium loop developed at KIT, Germany for component and material investigations and qualifications for high temperature applications in the CSP field.

[1] N. Krauter, A. Onea, G. Gerbeth et al., JNERS 9, 2023
[2] J. Fuchs, A. Onea, M. Böttcher, SolarPaces 2025
[3] S. Guth, T. Babinský, S. Antusch, et al., AEM 25 (16), 2023
[4] A. Onea, W. Hering, S. Ulrich et al., SolarPaces 2020

3D-printed prototype Inconel monolith channel

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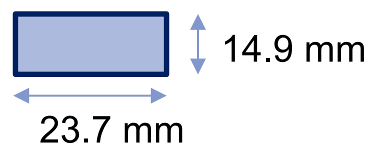
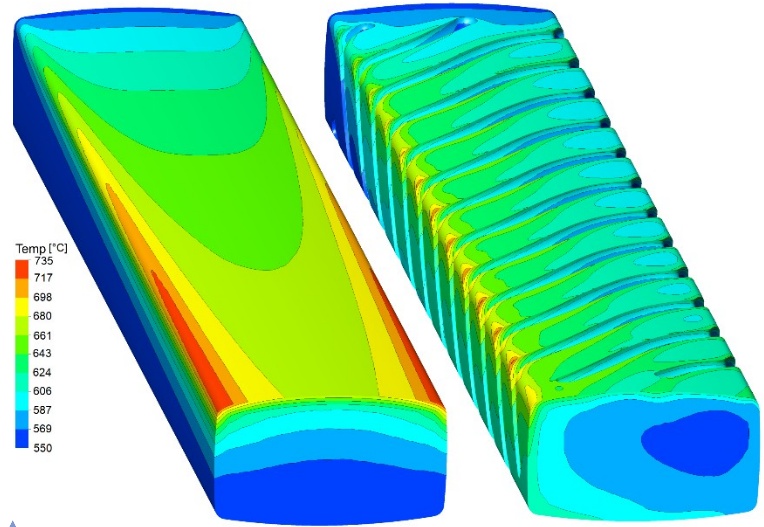
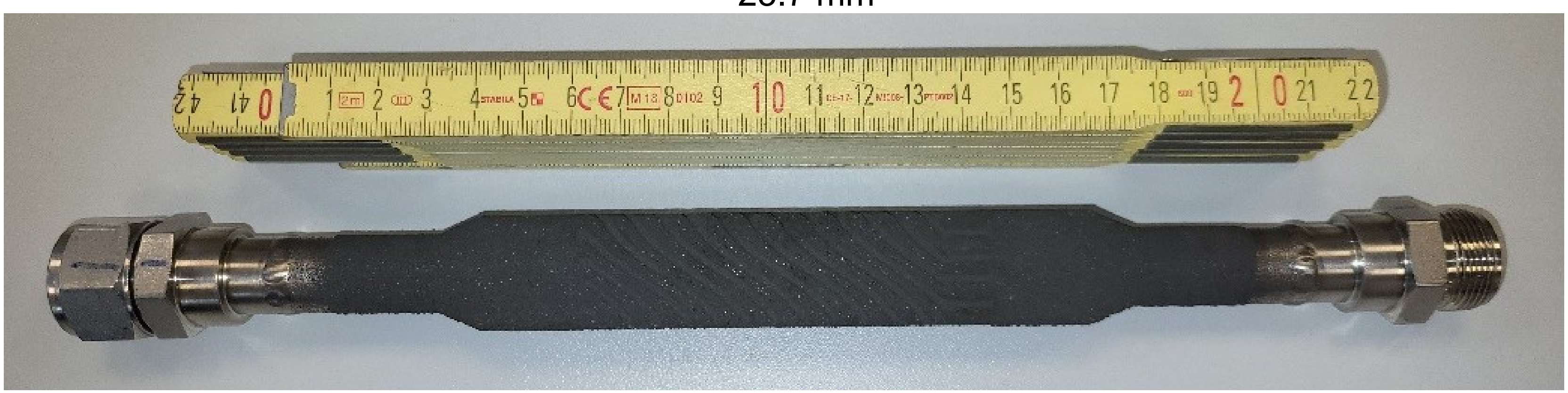
- Task: receiver material for high flux CSP;
- Procedure: Selective Laser Melting method, as well as the Cold Spray metal powder deposition;
- Material: Inconel 718 (powder);
- Dimensions; 14.9 x 23.7 x 200 mm^3 ;
- Inner and outer spiral rectangular channels: 2 mm;
- Cross-section rectangular duct:





J. Fuchs, M. Böttcher, SolarPaces 2022



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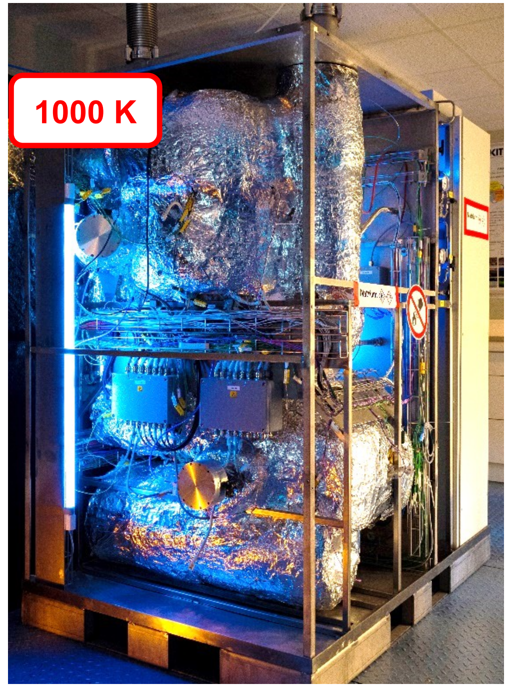
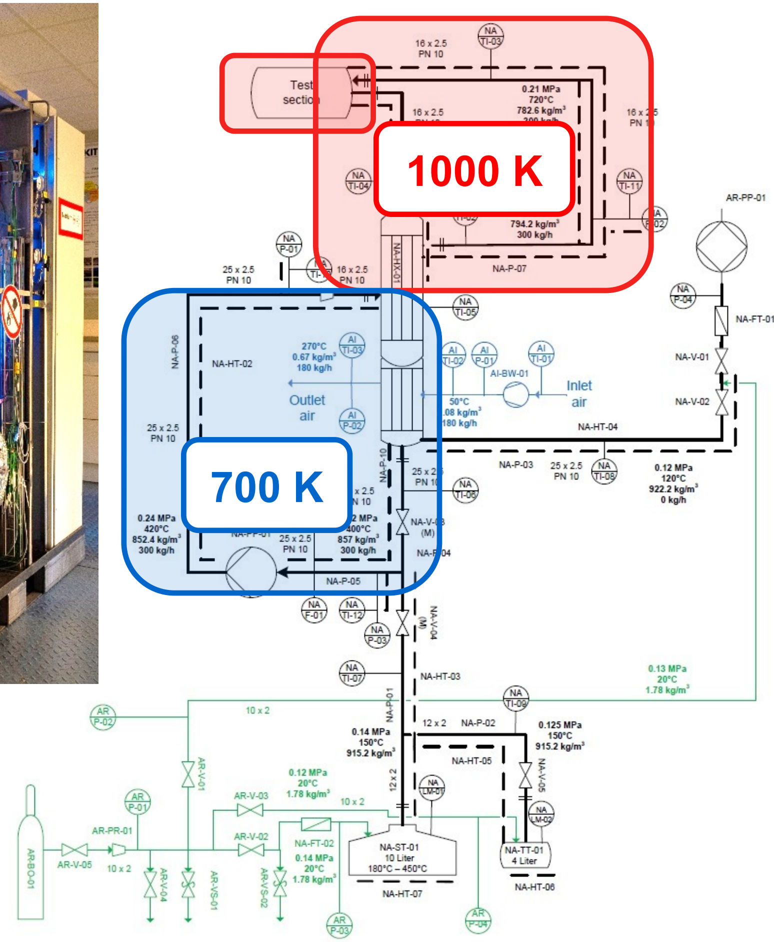
HEMCP AMTEC CENTER

SOLTEC – SOdium Loop to TEst materials and Corrosion

SOLTEC-2



- Na mass flow rate: 300 kg/h
  - Velocity TS < 4.8 m/s (Re = 28600, 300°C);
- Temperature:
  - Cold loop 450°C;
  - Hot loop 720°C;
- Max. pressure: 3.5 bar g
- Dimensions: 1.2×1.6×1.9 m^3
- Na inventory: ~ 14 L
- Main components:
  - 3kW Na-pump (permanent magnet pump)
  - 7.5 kW Na-air HX & 27 kW Na-Na heat recuperator,
  - Storage tank (15 L) = expansion tank (particular feature)
  - 6.7 kW high temperature heater



P&I diagram

Integration of the channel receiver in SOLTEC-2

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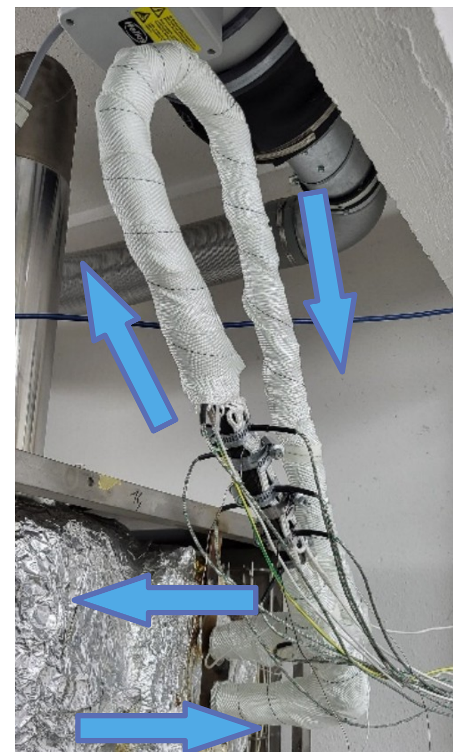
- Test of the prototype receiver in the atmosphere;
- Area front side: 30.8 cm2
- Heating wire on monolith channel (one side): 75 W -> q = 24.3 kW / m2
- U-form pipeline and straight pipeline: Inconel 718, also heated.
- Pipeline ID: 11 mm.



Instrumentation of the channel receiver

- T 8: outlet receiver, below
- T 7: receiver channel, front side
- T 6: receiver channel, back side
- T 5: receiver channel, front side
- T 4: receiver channel, back side
- T 3: receiver channel, front side
- T 2: inlet pipe, below
- T 1: inlet pipe, back side

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Experimental data: influence of the heater

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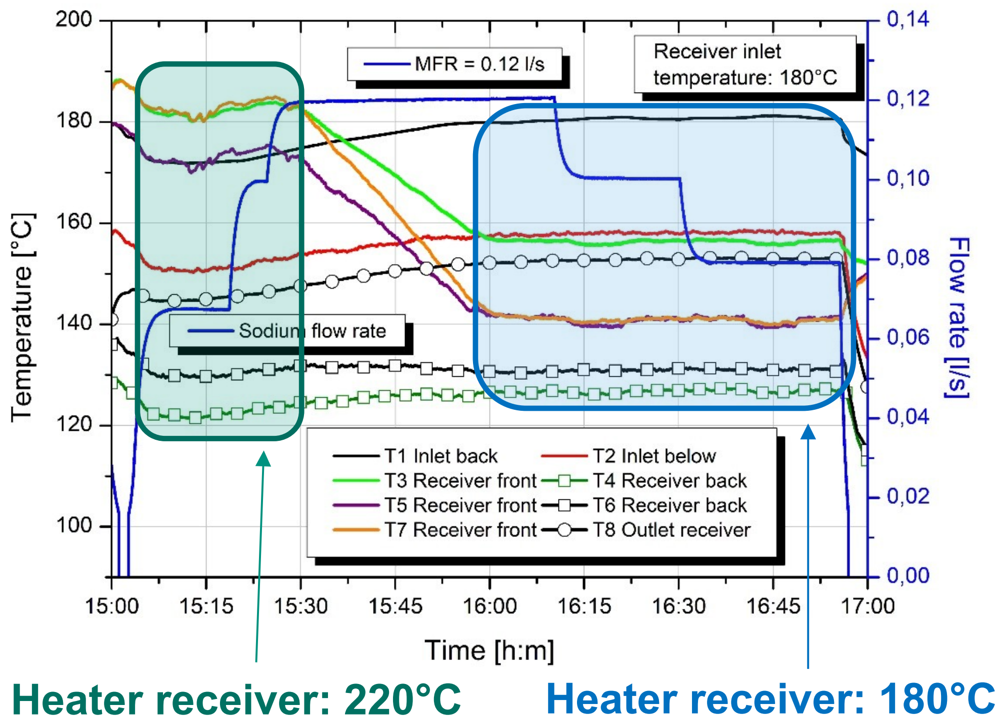
- Average data monolith rectangular channel:
  - Re (MFR = 0.12 l/s): 14295
  - Vel (MFR = 0.12 l/s): 0.46 m/s
- Change of heat flux applied on the front side: no significant influence on the temperature distribution on the back side of the monolith channel;
- Change of sodium flow rate: no significant impact on the temperature distribution in the receiver;

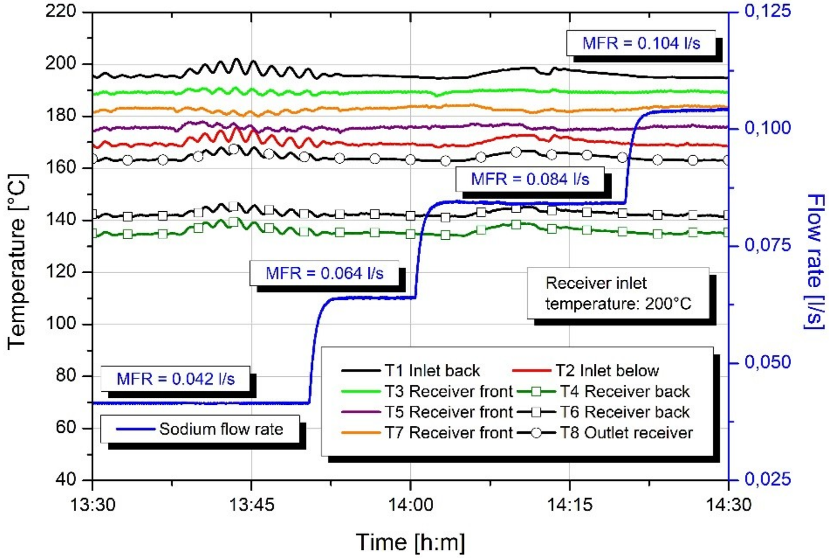


- Temperature oscillations are due to the oscillations of the high temperature heater in the SOLTEC facility.
- Even at max. power of the heating wire, the temperature on the front side of the receiver < 200°C.

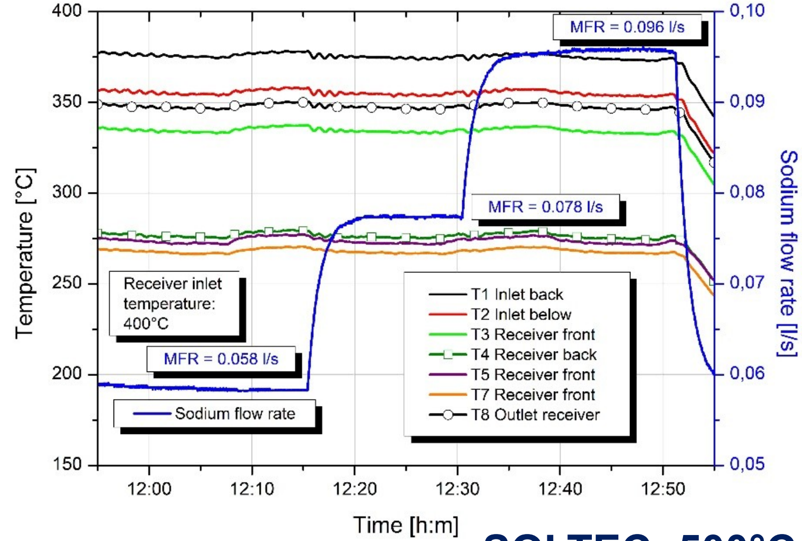
Experimental data: influence of flow rate

- Channel heater set to 180°C

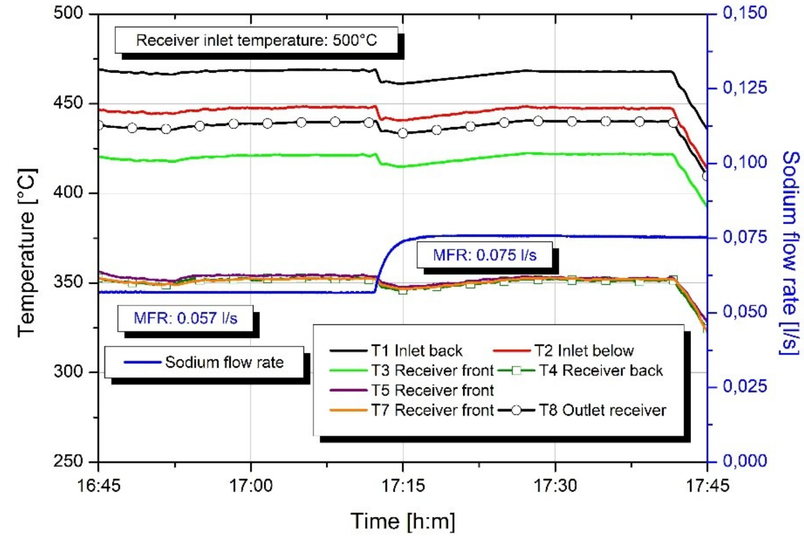
SOLTEC: 200°C



SOLTEC: 400°C



SOLTEC: 500°C



- Reynolds number: 8733 – 21834
- Velocities: 0.44 – 1.1 m/s
- Variation of the sodium flow rate: no significant influence on the temperature distribution on the channel.

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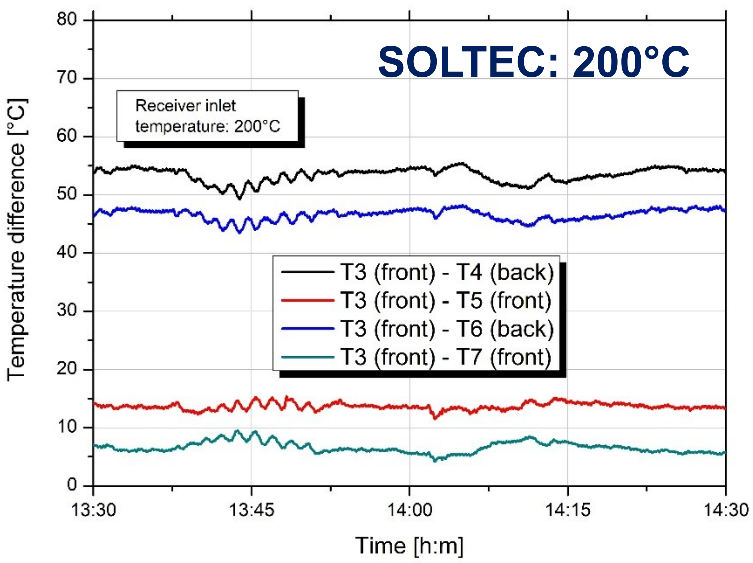
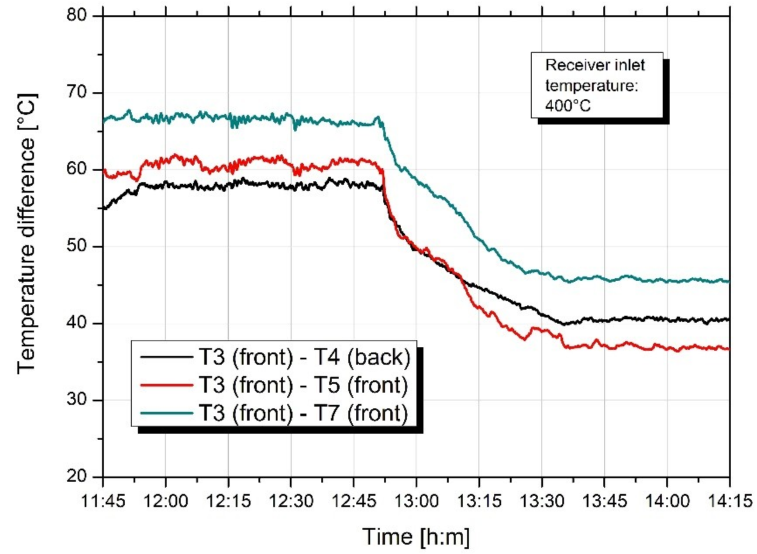
Temperature difference on the rectangular channel

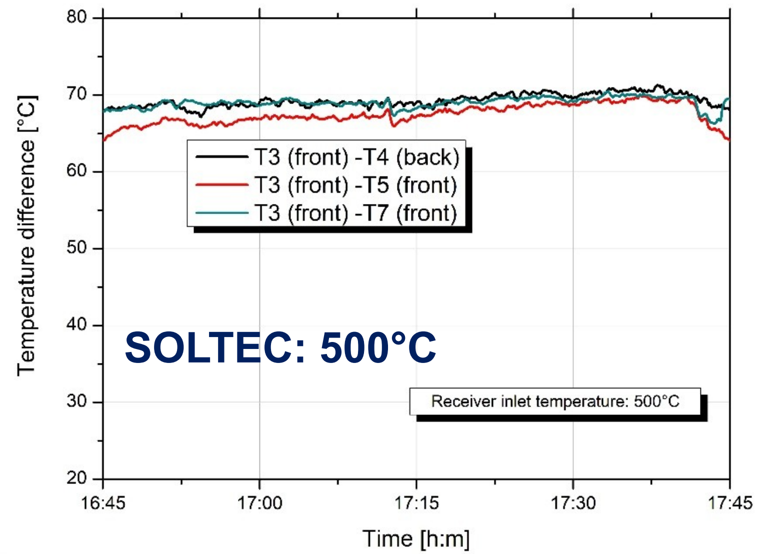
- Temperature difference on the front and back side of the receiver channel.



- Significant influence of the heater on the front side of the receiver on the temperature distribution in the front side for temperatures ≤ 200°C.
- The influence of the lateral heater diminishes at inlet temperatures > 200°C.

SOLTEC: 400°C





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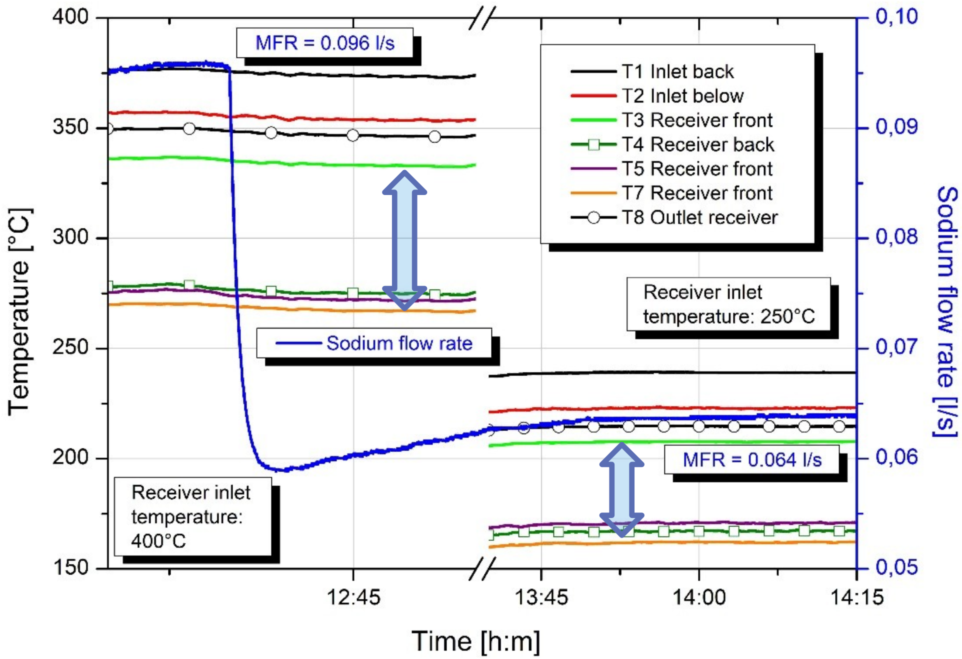
Influence of inlet temperature

- Inlet temperature: 250°C:
  - ΔT inlet-outlet (T3-T7): 45.6°C
- Inlet temperature: 400°C:
  - ΔT inlet-outlet (T3-T7): 66.1°C
- Inlet temperature: 500°C:
  - ΔT inlet-outlet (T3-T7): 69.2°C
  - ΔT inlet-outlet (CFD): 69.4°C

- When the influence of the side heater is negligible: almost constant temperature distribution along the flow direction and in azimuthal direction.

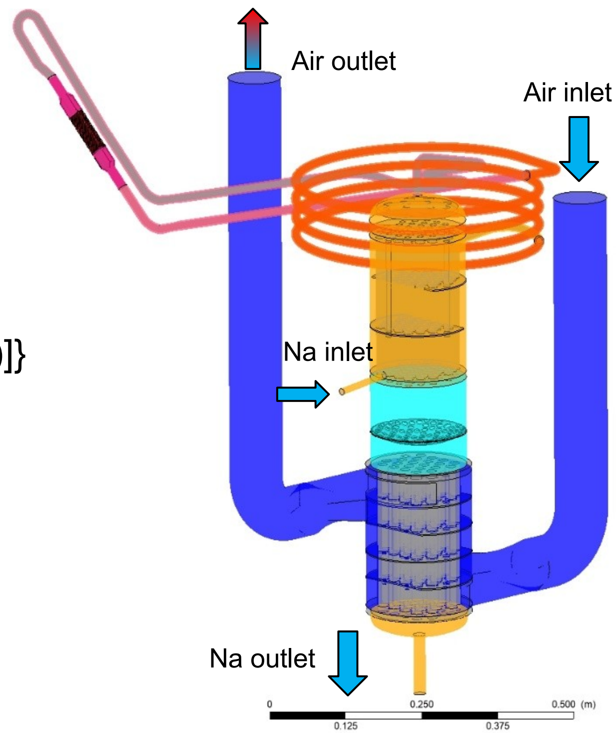


CFD Model

- Pointwise grid: 41.2 mio. cells (49% hexagonal, 45% tetrahedral, 3% pyramids, 3% prisms); y+ < 1 (regions of interest);
- ANSYS CFX 2024: Conjugate heat transfer model (Na, air, steel, Inconel 718);
- Air, Na, Inconel properties implemented as temperature dependent;
- Heat transfer model: thermal energy;
- TM: ω-RS (Na) and SST (air);
- Turbulent Prandtl number:

  Pr_{turb} (Air) = 0.85

  $Pr^{-1}tb(Na)=0.014\ Re^{0.045}\ Pr^{0.2}\ \{1-\exp[-1/(0.014\ Re^{0.045}\ Pr^{0.2})]\}$
  [Aoki, 1963]
- Thermal losses based on exp. data



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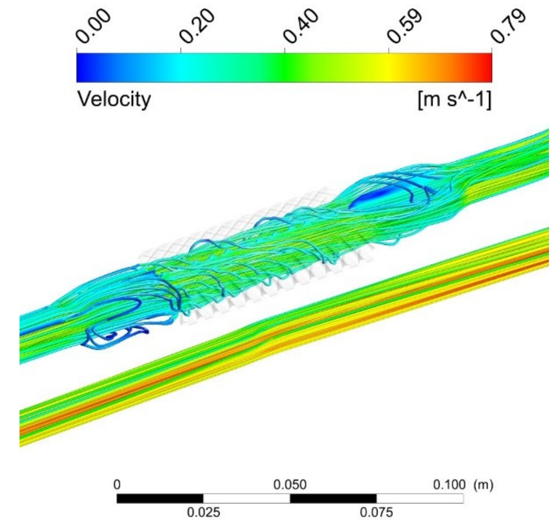
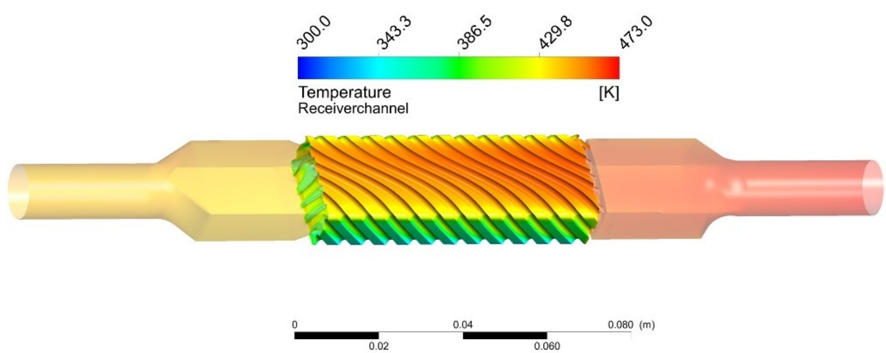
Validation of the numerical model

Location	T_{exp} [°C]	T_{CFD} [°C]	Absolute difference [°C]	δ [%]
T 1	195.1	192.2	2.9	1.5
T 2	169.4	187.3	17.9	10.5
T 3	189.5	186.4	3.1	1.6
T 4	134.9	155	20.1	14.8
T 5	176	185.7	9.7	5.5
T 7	183.3	379.7	6.6	3.6

Temp. inlet receiver: 200°C
Temp. heater receiver front side: 180°C
$\dot{m}_{Na}$ = 194 kg/h
Mean inlet temperature heated part: 191.8°C
Mean outlet temperature heated part: 174.6°C

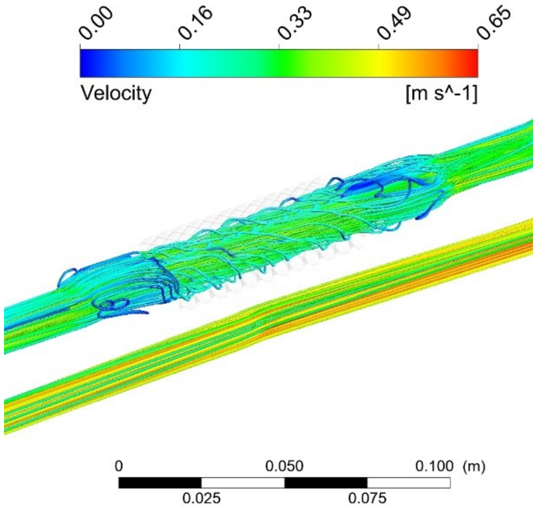




Good agreement obtained between the numerical results and the experimental data.

Validation of the numerical model

Location	T_{exp} [°C]	T_{CFD} [°C]	Absolute difference [°C]	δ [%]
T 1	469.4	462.2	7.2	1.5
T 2	448.3	438	10.3	2.3
T 3	422	429.1	7.1	1.7
T 4	353	352.3	0.2	0.7
T 5	355	350.6	4.4	1.2
T 6	395	375	20	5.1
T 7	353	379.7	26.7	7.6

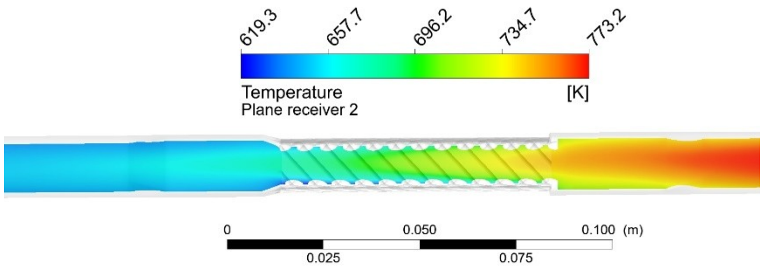


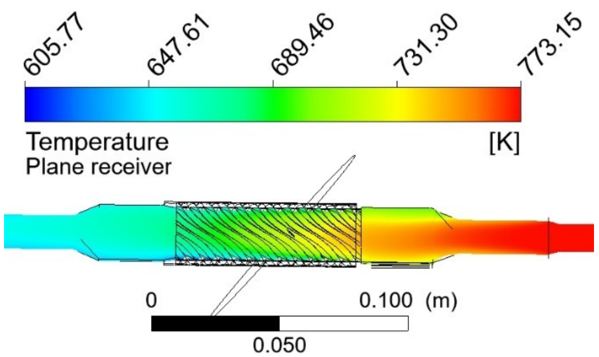
Temp. inlet receiver: 500°C

$\dot{m}_{Na}$ = 153 kg/h

Mean inlet temperature heated part: 446.1°C

Mean outlet temperature heated part: 376.7°C





Good agreement obtained between the numerical results and the experimental data.

Numerical investigations

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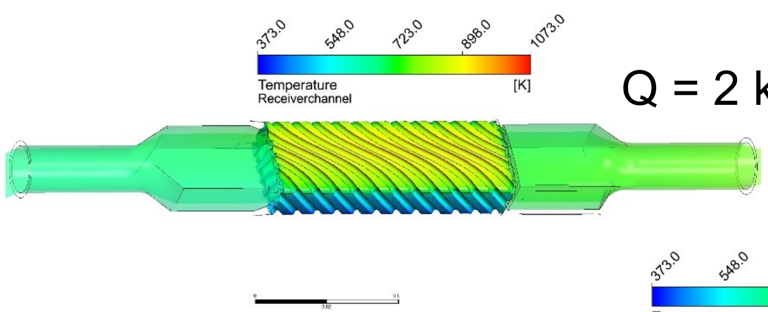
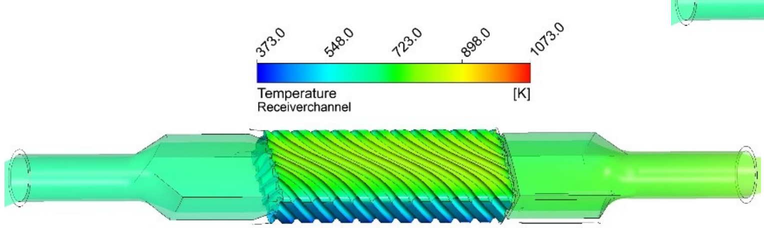
Location	T_{exp} [°C]	T_{CFD} [°C]	T_{CFD} [°C] Q = 1 kW q = 439 kW/m²	T_{CFD} [°C] Q = 2 kW q = 877 kW/m²	T_{CFD} [°C] Q = 3 kW q = 1316 kW/m²
T 1	469.4	462.2	462.2	462.2	462.2
T 2	448.3	438	438	438	438
T 3 front	422	429.1	429.1	429.1	429.1
T 4 back	353	352.3	354.1	356.3	358.5
T 5 front	355	350.6	556	647.9	730.1
T 6 back	395	375	391.5	400.2	409.1
T 7 front	353	379.7	405.6	420.5	435.1
T inlet rec		446.1	448.4	449.5	450.6
T out rec		376.7	399.3	411.9	424.4
ΔT in-out		69.4	49.1	37.6	26.2

Temp. inlet receiver: 500°C

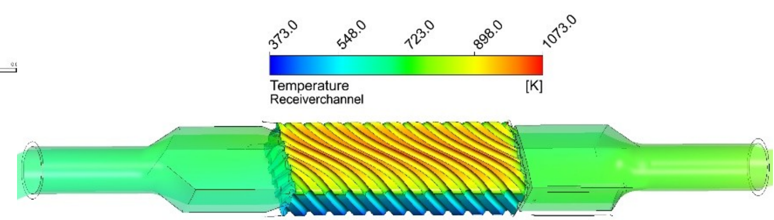
$\dot{m}_{Na}$ = 153 kg/h



Q = 2 kW



Q = 1 kW



Q = 3 kW

Nusselt number

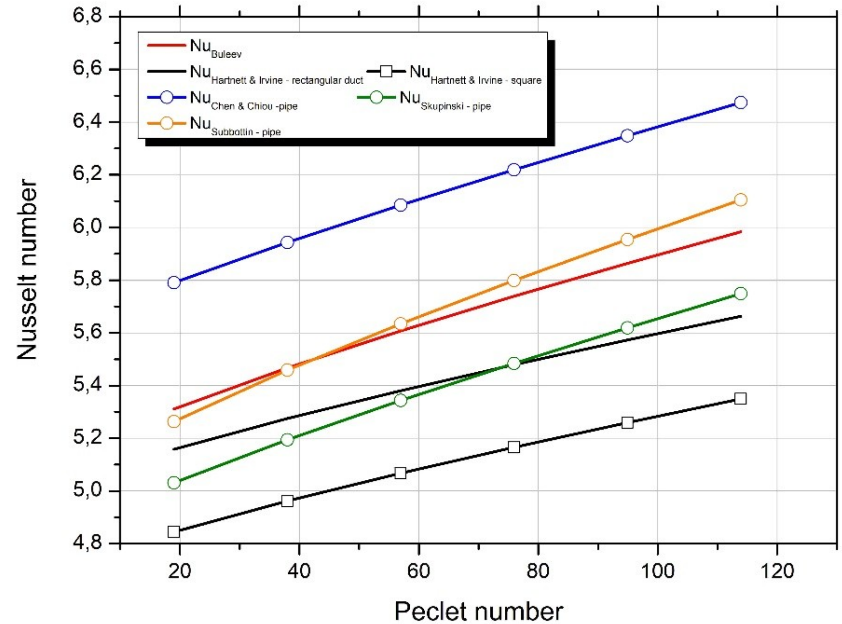
Rectangular ducts:

Hartnett & Irvine (1957):

$Nu_{H\&I} = 2/3\ Nu_{slug} + 0.015\ Pe^{0.8}$, $Nu_{slug} = 7.5$

Buleev (1959):

$Nu_B = 5.1 + 0.02\ Pe^{0.8}$



Nusselt number	Re=11439	Re=25966
Peclet number	44.7	101.5
Buleev (1959)	5.518	5.9
Hartnett & Irvine (1957)	5.314	5.6

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Conclusions

- Succesfull experimental investigations of a 3D-printed Inconel 718 prototype monolith rectangular duct with spiral channels up to 500°C performed in the SOLTEC-2 facility;
- Good tightness of the 3D-printed Inconel prototype;
- Successful validation of the numerical model against experimental data. Good agreement obtained for the temperature field;
- Outlook:
  - Further tests planned with higher power heater and at temperatures above 500°C;
  - Prototypical receiver with larger dimensions for the heat transfer area planned.

Thank you for your attention!

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