SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Analysis and Simulation of CSP and Hybridized Systems

https://doi.org/10.52825/solarpaces.v3i.2399

Published: 26 Nov. 2025

CFD Study on a Breadboard Receiver With Inserted Spiral Structures and Sodium as Coolant

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Abstract. In this work CFD studies about tubular CSP (Concentrated Solar Power) receivers with heat fluxes of more than 4 MW/m^2 and liquid sodium as heat transfer medium are presented. A significant improvement of heat transfer conditions is achieved by using spiral type ribs at the inner pipe walls. Furthermore, a comparison of receivers made of Inconel 690 and Niob is shown.

Keywords. CSP Receiver, CFD, Spiral Ribs

1. Introduction

The conversion of sunlight into thermal energy is considered to be very efficient, especially with high concentration rates of the sunlight and high resulting temperatures at the receiver. The heat flux can achieve values of more than 4 MW/m^2. Suitable fluids for handling the heat transfer at those conditions need to have a high thermal conductivity such as liquid sodium. High fluid temperatures are advantageous for a long-time storage in a tank and a final use as high temperature heat source for industrial applications.

One main parameter for the receiver design are maximum temperatures inside the receiver channels due to the onset of sodium boiling which must be avoided due to possible damage of the receiver.

Basic components of standard tubular receivers are pipes in a parallel, regular arrangement with a half side thermal irradiation that leads to a thermal stratification within the coolant.

In this contribution, computational fluid dynamical studies of receivers with an irradiated area of 0.8 m x 1 m are shown. While the first receiver is constructed by ordinary pipes, the second one uses pipes with spiral type ribs, see Fig.1.

The receiver includes 32 individual rods with an outer diameter of 24 mm and a minimum wall thickness of 1.75 mm. The rods are collected by inlet and outlet boxes. For both cases, a radiation profile with a maximum of approximately 4.3 MW/m^2 in the center is used, see Fig. 2. The radiation distribution was provided by Vast Solar, Australia [1]. The receiver is irradiated with a total power of about 1.6 MW. Other basic parameters are the sodium inlet temperature of 550 °C and the average outlet temperature of 750 °C. For safety reasons the system pressure should be close to atmospheric pressure, which means a boiling temperature for sodium of about 890 °C. This may provide problems for ordinary pipes because boiling of sodium may cause local pressure peaks and a final receiver damage. Coolant mixing can be improved by using spiral type rib structures or twisted tapes [2]. Those structures generate a rotating superposed flow with rotational velocities up to 40% of the main axial component.

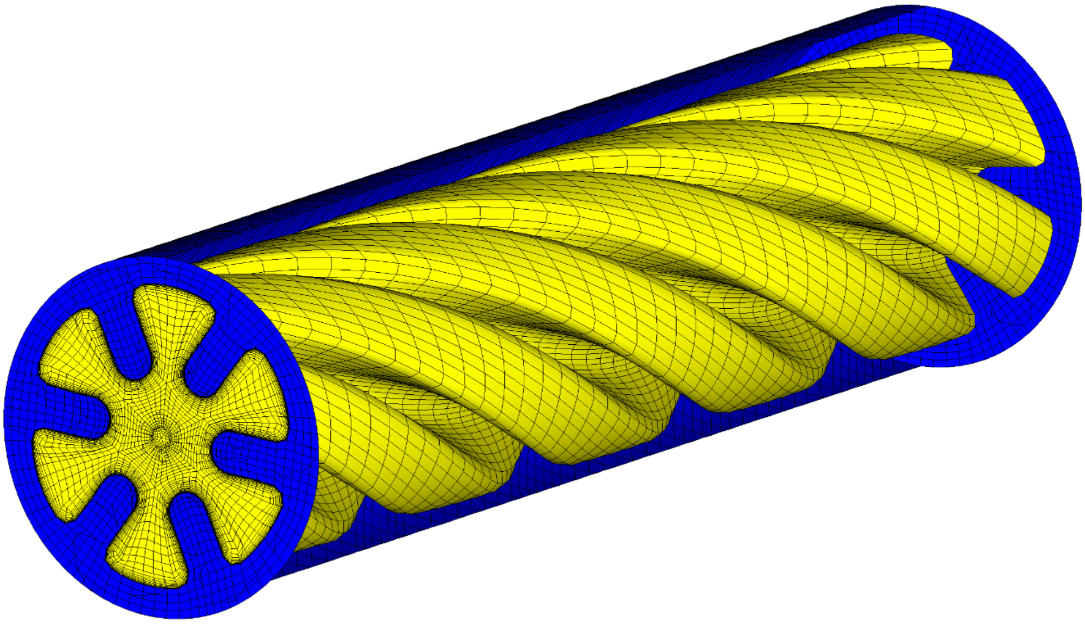

Figure 1. *Mesh detail of a receiver rod with spiral ribs*

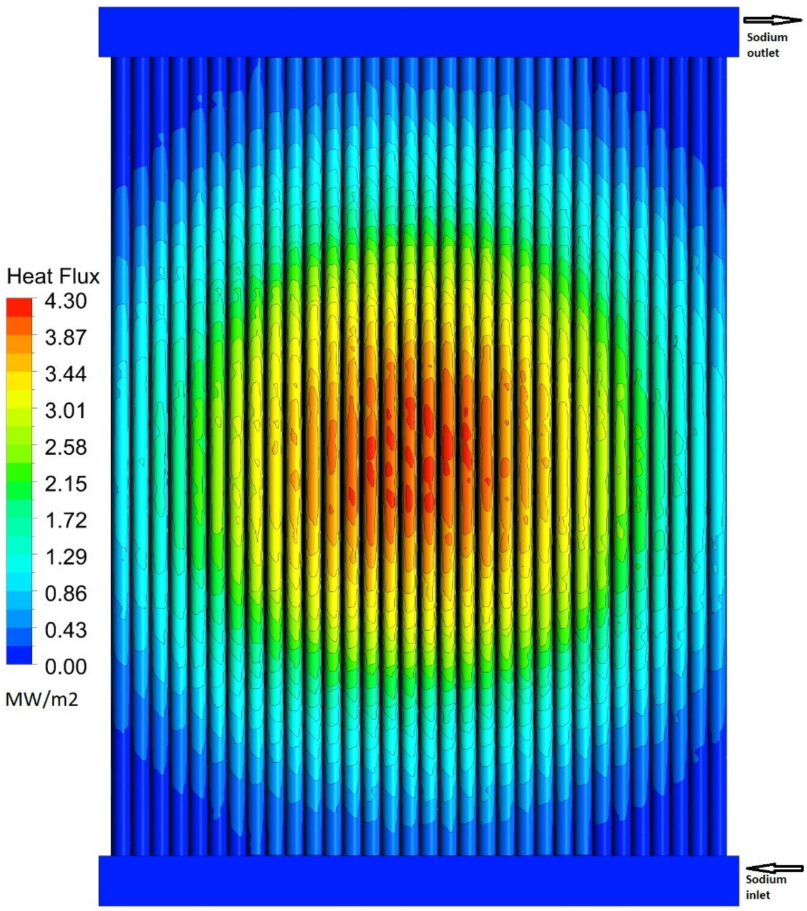

Figure 2. *The radiative heat flux*

This additional swirl transports cold fluid from unheated regions towards heat impacted areas and improves thermal mixing. It must be mentioned that the effectivity of those structures is highest for liquid metal fluids such as sodium, where the thermal boundary layer is significantly larger than the momentum layer. Studies have shown that ribs are more effective for heat transport into central pipe regions especially if a solid material with high thermal conductivity is used. Especially if Niob is used -as presented in this paper-, ribs are in advance for obtaining more homogeneous temperature distributions within the coolant.

2. Model description

For all cases steady state conditions are assumed and RANS simulations by using ANSYS CFX were performed. An SST model [3] was used for the simulation of turbulence. The individual mass flow in each pipe was adjusted due to the individual pipe dependent incoming radiation. The total power for each pipe – by taking radiative losses into account in terms of radiation of all outer surfaces into the background by Stefan-Boltzmann law – varies between 11 KW in the outer positions and 67 KW for the central pipes, so that an individual mass flow adaption was necessary to obtain nearly similar average temperatures at the vertical upper end of the pipes, where they are entering into the upper collecting box.

As boundary condition an inlet temperature of 550 °C and a total mass flux of 6 kg/s is assumed. The desired average outlet temperature is 750 °C.

Table 1. *Material properties.*

	Inconel 690	Niob	Sodium
Melting point [°C]	1343 - 1377	2477	$98/890_{boil,\ 1bar}$
ρ [kg m^{-3}]	8190	8572	922 – 760
Cp [J kg^{-1} K^{-1}]	471 – 711	175 – 318	1316 –1266
λ [W m^{-1} K^{-1}]	13.5 - 30.1	54 – 69	88 – 55
Temp. range [°C]	100 -1000	100 -1000	100 – 800

In the CFD model, individual loss coefficients dependent on the pipe location and the local radiative power were introduced. Because of upcoming buoyancy effects at peripheral pipe positions, a Boussinesq approximation was used. Sodium with temperature dependent properties was implemented in connection with a modified constant turbulent Prandtl number of 1.5 [4] used for calculation of turbulent heat transfer based on Reynolds analogy. Also, a temperature dependent thermal conductivity of receiver material was implemented as shown by Table 1.

The mesh of the rods is generated by structured hexaeder cells, while for the lower and upper collecting volumes a hybrid meshing technic is performed, see Fig. 1. About 60 Mio cells are used for the receiver with internal ribs.

3. Results

Fig. 3 shows receiver surface temperatures at the heat impacted outer surface. The location of temperature maximum is slightly shifted in vertical direction compared with the location of highest heat impact, which is consequence of convective heat transfer inside the receiver. For the case of ordinary pipes and Inconel as solid material the maximum temperatures do not allow a long-term operation of the receiver because of vicinity to the melting temperature of Inconel, see Table 1. The material properties are taken from [5], [6] and [7]. The increase of mass flow or the use of a smaller pipe diameter is not an option because of reduced outlet temperatures and pressure loss increase.

The use of inner spiral ribs reduces the temperature maximum of approximately 70 °C which is about 150 °C below the melting point of Inconel but still a problem for a long-term receiver operation. A solution is the replacement of Inconel by Niob, which has good chemical resistance properties against sodium corrosion. The outer surface of a Niob receiver would require a special coating due to possible reactions with oxygen at higher temperatures. The advantage of Niob is its significant higher thermal conductivity compared with Inconel, which reduces the surface temperatures significantly from 1200 °C to 1000 °C in combination with a material melting point close to 2500 °C. Finally, a mechanical analysis for thermal stress and material creeping is required, which is not part of this investigation.

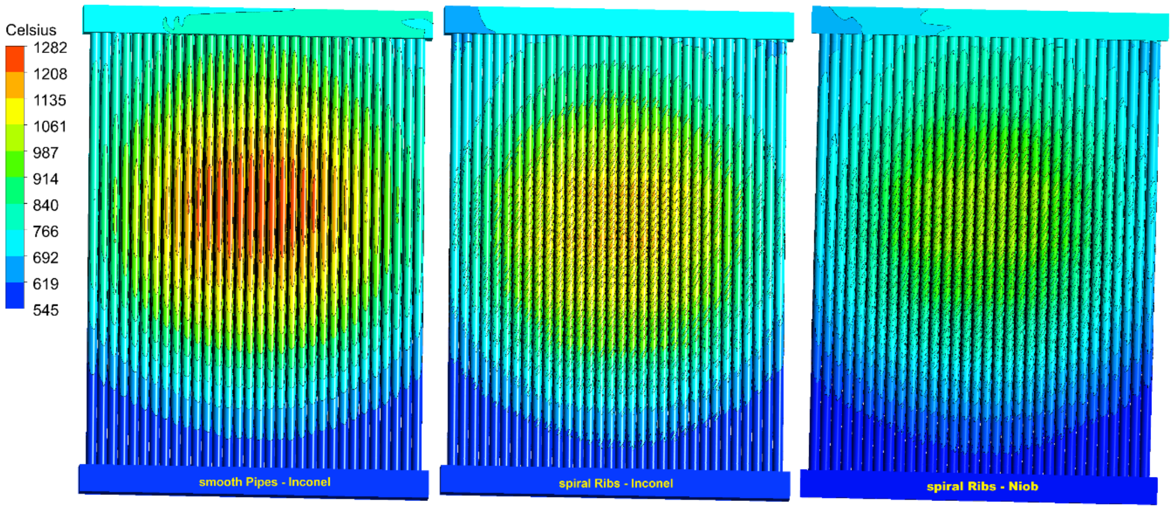

Figure 3. *Receiver surface temperature*

Fig. 4 shows temperature distributions in the vertical center of the receiver for a pipe with maximum heat impact. At the specified conditions it is not possible to operate the receiver constructed by ordinary pipes without avoiding local sodium boiling (890 °C at 1 bar). While the temperatures for the ordinary pipes increase locally significantly above the boiling temperature up to 1057 °C, pipes with spiral ribs reach in maximum about 870 °C. The reason therefore is the generated swirl of the spiral ribs which transports cold sodium from the unheated side of the rod towards the heat impacted upper locations. As consequence, the heat transport is improved which finally leads to tower temperatures in the solid parts which reduces the thermal stress and improves the safety margin for the receiver operation.

For the investigated cases the expected average outlet temperature of 750 °C is nearly reached by 743 °C for the ordinary pipes and 744 °C for the case with ribs. The reason for the slightly higher temperature is found in the reduced outer surface temperature. For all models, losses by thermal radiation into the background are considered. Therefore, an emission coefficient of 0.6 was assumed. As consequence, the reduction of radiative losses leads to higher coolant outlet temperatures which means a higher thermal efficiency of the receiver. The CFD models calculate radiative losses of 0.135 MW for ordinary pipes and 0.130 MW for pipes with ribs which is about 8.5% of the concentrated solar radiation.

Further improvements are possible mainly by the use of solid materials with a higher thermal conductivity than Inconel such as Niob. The outer surface temperatures are reduced significantly by about 180 °C as consequence of the higher thermal conductivity compared with Inconel. In addition, the ribs themselves become more effective for the heat transfer towards the inner parts of the pipe. The coldest central part of the ribbed channel is smallest in case of Niob as receiver material. In Table 2 a comparison of some essential receiver data is given.

Table 2. *Comparison of receiver data.*

	Pipes (Inconel)	Spiral ribs (Inconel)	Spiral ribs (Niob)
Tmax,surface [°C]	1282	1215	1029
Tmax, Sodium [°C]	1047	871	861
Total power [MW]	1.46	1.46	1.48
Heat loss [MW]	0.14	0.13	0.09

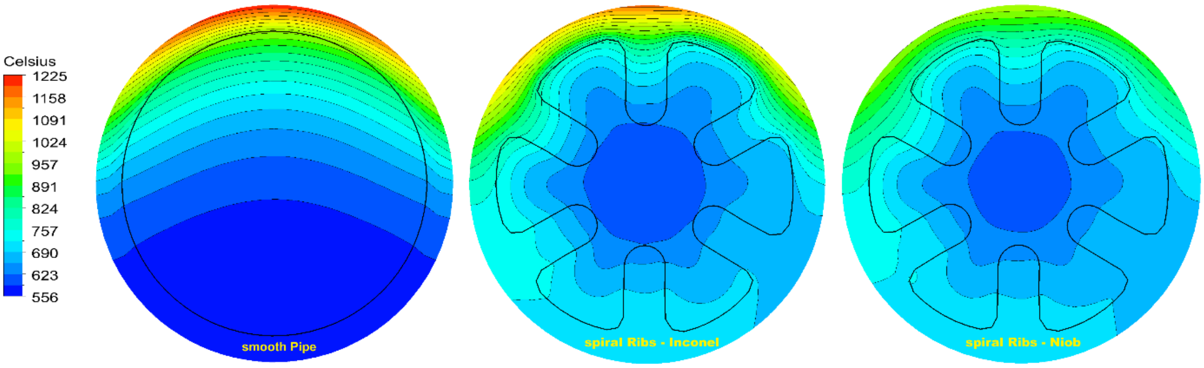

Figure 4. *Temperature distribution at receiver center*

As previously mentioned, the configuration of spiral ribs and Niob is clearly the best option because of lowest surface and sodium temperatures. Furthermore, lower surface temperatures lead to lower radiative heat losses of the receiver surface into the background. In all cases, a complete absorption by the irradiated receiver surface is assumed, which is conservative concerning the operational safety of the receiver.

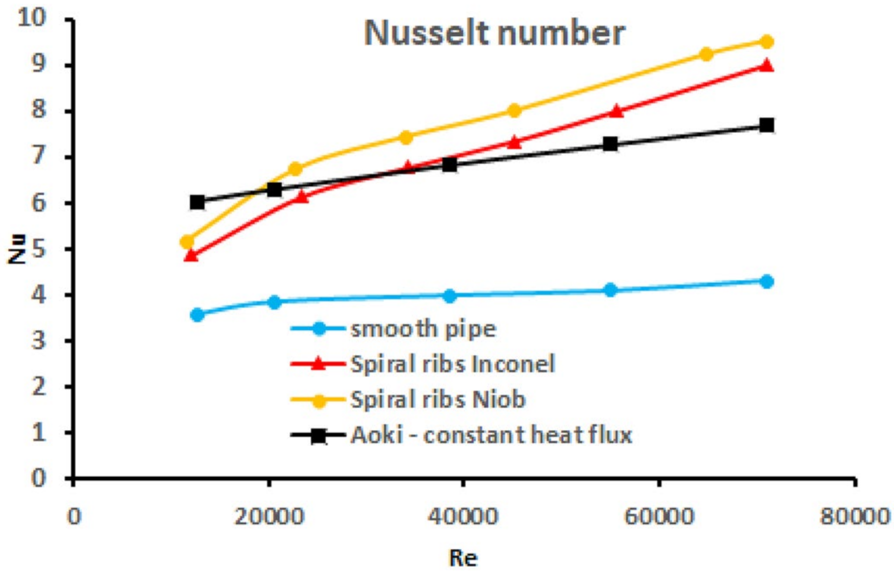

Figure 5. *Central Pipe Nusselt number*

Fig. 5 presents an analysis of Nusselt numbers for the central pipe – for a line in the maximum of the heat impact averaged over the heated length. Compared with ordinary pipes the Nusselt numbers are increased up to a factor of 2 by using spiral ribs. Additional increase is achieved by using Niob, which improves the heat transfer by the ribs into the central coolant channel as previously mentioned. A comparison with correlations to be found in literature – such as by Aoki [8] – is difficult because of different boundary conditions. While the presented cases are non-constant asymmetric heated, the Aoki correlation is valid for a constant heat flux which leads to deviations.

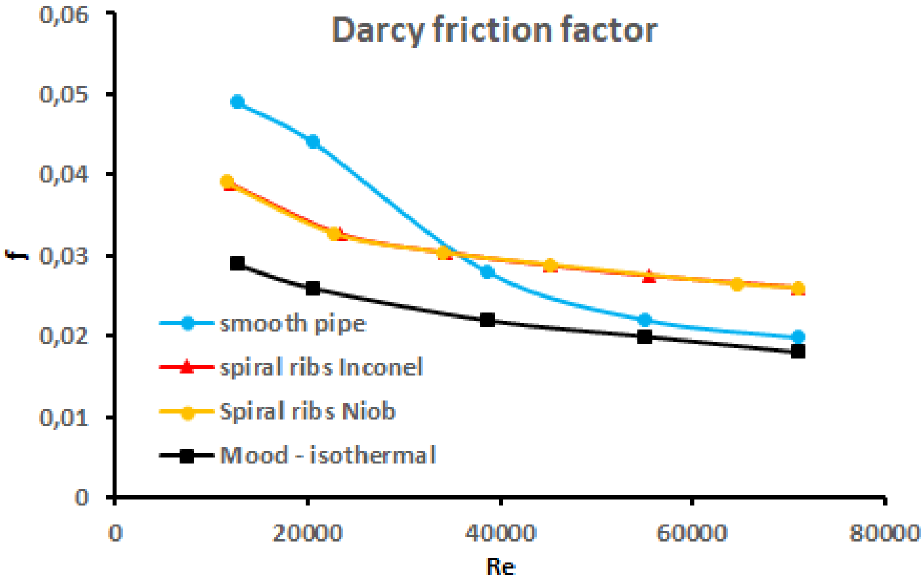

Figure 6. *Central pipe friction factor*

A comparison of Darcy friction factors [9] is given by Fig. 6. The cases are compared with a correlation from the Moody diagram for isothermal, smooth pipe flow. The spiral rib cases show only a low dependency on the receiver material and are about 25% larger as those for isothermal pipe flow. The heated pipe flow case shows an unexpected behavior at Reynolds numbers less than 35000, where upcoming buoyancy effects lead to increase of friction factors beyond the values of the ribbed cases. The reason is given by a local heat up of the coolant mainly in the circumferential central zone of the CSP impact, which leads to local buoyancy effects mainly in case of less turbulent heat transfer at lower Reynolds number.

The data presented within Fig. 5 and 6 is obtained from standalone single pipe studies mainly because of numerical efficiency. Furthermore, the heat flux impact was scaled by Reynolds number in order to keep sodium below boiling while running cases at lower Re.

4. Summary and conclusions

The use of spiral ribs improves heat transfer conditions significantly and seems to be a possibility for an operation of a tubular CSP receiver under the specified conditions. The use of Niob instead of Inconel reduces surface temperatures and would allow to use even higher CSP fluxes. First studies indicate fluxes up to 20 MW/m^2 in combination with an implementation of a solid rod axis.

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

The authors acknowledge the financial support received from the Helmholtz Association, Research Field Energy (funding number 38.04.02). The data used in this paper is available from the first author. J. Fuchs provided essential support in receiver design and the selection of materials. The authors declare that they have no conflicts of interest with respect to this study.

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