HEAT TRANSFER INVESTIGATION OF THE SODIUM FLOW IN THE 720°C SOLTEC FACILITY

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ABSTRACT

The 1000K SOLTEC-2 sodium loop is a test facility developed for investigations of corrosion and erosion of materials in hot sodium above 720°C, as well as tests of components for high temperature applications. The present study investigates the flow dynamics and the heat transfer in the high temperature branch of the facility and in the core component, which is a sodium-sodium heat recuperator coupled directly to a sodium-air heat exchanger. The experimental data available for the temperature field was used to validate the numerical models that were developed in ANSYS CFX. The Nusselt number was calculated using an empirical correlation proposed in literature. The heat transfer coefficient obtained from the Nusselt number was also compared against the heat transfer coefficients from the numerical model. The thermal effectiveness of the heat recuperator for the usual sodium flow rates is reported.

INTRODUCTION

The application of liquid metals, especially sodium, as heat transfer fluids in a solar tower power plant received increased interest in the last decade [1-4]. In this frame, adequate structural materials have to be developed and qualified to clarify their behaviour regarding the corrosion/erosion and their creep fatigue limits at sodium temperatures above 700°C, as highlighted in [5,6]. Given the wide range of experimental tasks planned, the SOLTEC experimental family of facilities have been developed and erected at the Karlsruhe Institute of Technology. Three similar facilities have been constructed, each having its own test experimental purpose. SOLTEC-1 is planned for low-fatigue investigations of new materials, while SOLTEC-2 for corrosion and erosion studies of materials in hot sodium. For both facilities, the test probe can be further heated in the test section above a temperature of 700°C that is provided by the base loop. Besides material qualification, tests of components and sensors for high temperature applications are foreseen and have already started in the frame of different projects.

SOLTEC-2 facility has been operated more than 15 h at the maximal operating temperature of 720°C during the set-into-operation phase. At the core of the facility, between the low and high temperature branches a sodium-sodium heat recuperator is directly coupled to a sodium-air heat exchanger. The present study focuses on the numerical investigation of the high temperature branch and the sodium-air heat exchanger. The experimental data obtained from SOLTEC-2 facility were used to validate the numerical model of the combined sodium-sodium heat recuperator – sodium-air heat exchanger.

NOMENCLATURE

c_p	[J/K]	Heat capacity
k	[W/mK]	Thermal conductivity
$\dot{m}$	[kg/h]	Mass flow rate
Nu	[-]	Nusselt number
Pe	[-]	Peclet number
Re	[-]	Reynolds number
T	[K]	Temperature
$y+$	[-]	Non-dimensional distance to the wall

Special characters

α	[W/m^{2}K]	Heat transfer coefficient
δ	[%]	Percentage difference
ε	[%]	Thermal effectiveness

Subscripts

exp	Experimental
fl	Fluid
in	Inlet
max	Maximum
out	Outlet
t	Turbulent
th	Theoretical
0	Ambient or reference

Acronyms

CFD	Computational Fluid Dynamics
SOLTEC	SOdium Loop to TEst materials and Corrosion

DESCRIPTION OF THE SOLTEC EXPERIMENTAL FACILITY

The SOLTEC facilities (see Figure 1) are similar loops layout for a maximal temperature of 720°C at an overpressure of 3.5 bar. The maximal specified mass flow rate is 300 kg/h. The loop has an 8-shape configuration, a low temperature side in the bottom part of the 8-shape and a high temperature side in the upper part. The low temperature branch is limited in operation to ~450°C and contains the sodium pump and the sodium flowmeter. The high temperature branch contains a

6.3 kW high temperature helical heater and the test section. At the interface between these branches a 27 kW sodium-sodium heat recuperator is connected directly with a 7.5 kW sodium-air heat exchanger, providing a compact arrangement. A side branch is connected to the low temperature branch, and contains the vacuum pump and the sodium-argon interface. As an innovative solution, the storage tank is used for both storage and sodium expansion, therefore eliminating the need of a dedicated expansion tank. Argon is used as a cover gas to inhibit the sodium oxidation and for pressure monitoring during all operation procedures. Since the loop has a compact size of 1.2 × 1.6 × 1.9 m^3 it can be operated in a regular liquid metal laboratory. Prior to the filling operation, the entire sodium loop is evacuated excepting the sodium storage tank, so that the filling with sodium can be performed under vacuum.

Figure 1 View of the SOLTEC-2 facility (with safety lateral walls removed)

Several safety measures were implemented and the layout of the facility followed a safety-by-design approach. Any sodium-water contact is completely eliminated and the less hazardous sodium-air contact can possibly occur only in case of sodium leakages through material cracks. To handle this event, a leakage detection system has been mounted that covers all sodium parts. Furthermore, the amount of sodium is limited (e.g. in the high temperature side to only ~0.6 L) and the operational pressure is just slightly above atmospheric pressure, so only a small amount of sodium can potentially exit the loop. Even in this scenario, the possible fire occurring will be extinguished either by argon ingestion or by lack of oxygen, since the entire loop is encapsulated in a metallic frame (removed in Figure 1 for visualization purposes). At any critical malfunction, an emergency drainage is initiated and the high temperature heater and the sodium pump have a dual independent surveillance (PLC system and sensors) that can initiate the emergency drainage if required.

The piping and instrumentation diagram of the facility is presented in Figure 2, while the sodium-sodium heat recuperator/sodium-air heat exchanger is presented in Figure 3. Both heat exchangers are counter current type, the heat recuperator contains Inconel pipes, due to the expected temperatures that are higher than 550°C, while the sodium-air heat exchangers contains stainless steel pipes. The connection of the heat exchangers is realized with a flange, avoiding by this solution the need of welding two different materials.

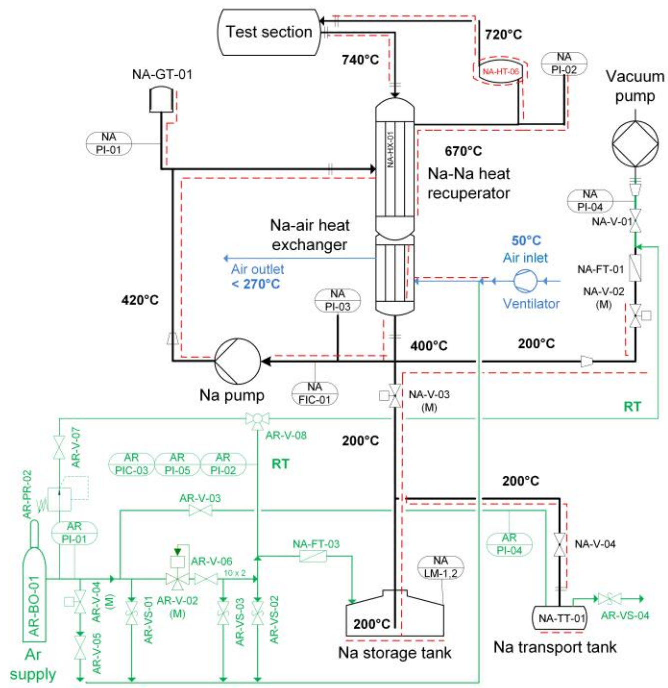

Figure 2 Piping and instrumentation diagram of the SOLTEC-1, -2 facilities

Figure 3 Combined sodium-sodium heat recuperator / sodium-air heat exchanger, the high temperature heater and the air cooling system

NUMERICAL MODEL

The central component of the facility, the heat recuperator/sodium-air heat exchanger and the U-shaped test sample were investigated numerically using ANSYS CFX 2021 R1. The numerical solution is based on a conjugate heat transfer approach considering the fluids, sodium and air, as well as the Inconel walls of the heat recuperator and the stainless steel walls of the heat exchanger.

All physical thermo-dynamical properties for air [7] and sodium [8], as well as for the materials for the walls have been implemented as temperature dependent. The air flow regime is turbulent and was modelled using the k-ω Shear Stress Transport (SST) turbulence model. Even up to the maximal mass flow rate specified and assuming a homogeneous flow distribution, the sodium flow is laminar in the tubes of the heat recuperator and the sodium-air heat exchanger. However, the sodium flow is turbulent in the pipelines and within the high temperature heater and was modelled using the Reynolds stress -ω turbulence model [9]. This Reynolds stress model uses the ω-equation instead of the ε-equation as the scale determining equation, since it allows for a more accurate near wall treatment. The model provides an automatic switch between a wall function to a low-Reynolds number formulation based on the mesh spacing [9]. Considering a mass flow rate of 137 kg/h and a uniform distribution of the sodium flow through the heat exchangers, the Reynolds numbers are 493 in the tubes of the recuperator and 300 in the sodium-air heat exchanger.

The ratio of the Grashof number to the Reynolds number is above unity, signifying that the buoyancy forces due to the temperature gradients have to be taken into account, and were considered in the model by employing the full buoyancy model available in ANSYS CFX.

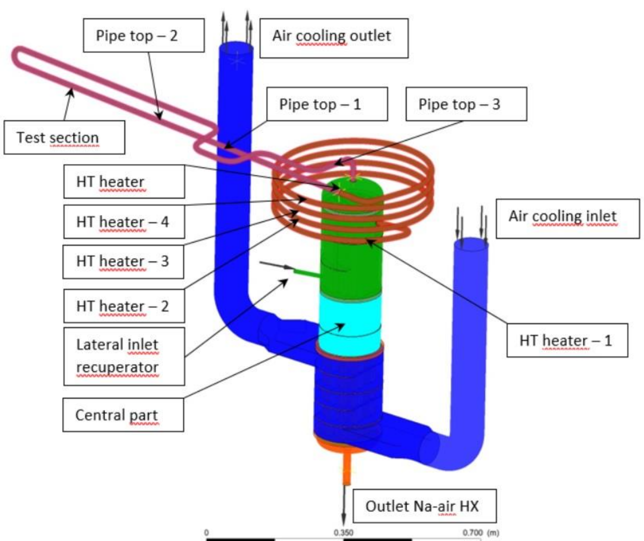

Figure 4 View of the CFD model exhibiting inlet and outlet conditions and positions of thermocouples

The mesh was generated using the Pointwise V18.3 software. The grid consists of 55 million cells, from which about 65% are hexagonal cells, 16% are tetrahedral cells and 18% are prisms. The walls were considered hydraulically smooth and the non-slip boundary condition was always applied. For an accurate estimation of the heat transfer the grid was constructed to obtain a non-dimensional distance to the wall of y+<1 in the regions where the heat transfer is of interest. The cell growth rate in the normal direction to the wall was set to 1.2, ensuring therefore a good resolution of the thermal boundary layer. The mesh skewness in cross-section through the sodium-sodium heat recuperator is presented in Figure 5. An effort was made to construct the grid using as many hexagonal cells as possible. In this sense, the grid inside and outside of the pipes was made using hexagonal cells, while a tetrahedral mesh was made in regions exhibiting a change in the geometry, which was difficult to be meshed with hexagonal cells.

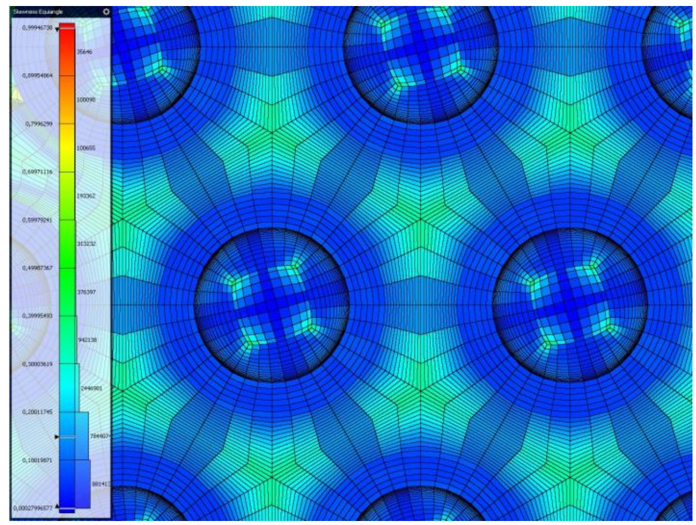

Figure 5 Mesh skewness in cross-section through the sodium-sodium heat recuperator

Boundary and Initial Conditions

The sodium enters laterally in the sodium-sodium heat recuperator in the central part of the model, as presented in Figure 4. It flows upwards meandering through the baffles and around the vertical tubes of the heat recuperator, while its temperature is increasing, and exists at the upper lateral side of the recuperator, where it enters the high temperature heater. There it is heated at the operating temperature. Following the U-pipe test sample, the hot sodium flows then downwards through the tubes of the heat recuperator, giving part of its thermal energy to the sodium coming from the low temperature branch. Further, the sodium enters directly the sodium-air heat exchanger, where it is cooled below 500°C to protect the sodium pump. The low temperature branch is held isothermal and the sodium is pumped from the outlet of the sodium-air heat exchanger to the cold inlet of the heat recuperator.

The experimental data obtained with the SOLTEC-2 facility for the temperature field and the sodium and cooling airflow rates were used as input data for the initial conditions in the CFD model, as summarized in Table 1. The heat losses through the thermal insulation were estimated and implemented in the model.

Table 1 Overview of initial conditions applied

Na mass flow rate [kg/h]	Sodium temperature at inlet [°C]	Air mass flow rate [kg/h]	Air temperature at inlet [°C]	Heat flux [W/m^2]
125	303	40.4	36.9	11 186
137	390	33.7	88.2	11 807

NUMERICAL ANALYSES

Validation of the Numerical Models

In order to validate the numerical model, the numerical results for the temperature field were compared against the experimental data. The location of the thermocouples considered for the comparison is displayed in Figure 4.

Table 2 Comparison between the experimental and calculated temperatures for a sodium flow rate of 125 kg/h

Location	T_{exp} [°C]	T_{CFD} [°C]	Absolute difference [°C]	δ [%]
HT heater – 1	648.4	655.8	7.4	1.1
HT heater – 2	659.8	660.4	0.6	0.1
HT heater – 3	681.9	686	4.2	0.6
HT heater – 4	690.8	687.9	2.9	0.4
HT heater	720.1	720	0.1	0
Pipe top – 1	717.4	719.3	1.9	0.3
Pipe top – 2	716.2	719.2	3.0	0.4
Pipe top – 3	712.2	717.6	5.4	0.8
Test section	709.3	718.7	9.4	1.3
Lateral inlet recuperator	307.1	303.4	3.8	1.2
Central part	369	366.8	2.3	0.6
Outlet Na-air heat exchanger	314.8	303.2	11.7	3.8

Table 3 Comparison between the experimental and calculated temperatures for a sodium flow rate of 137 kg/h

Location	T_{exp} [°C]	T_{CFD} [°C]	Absolute difference [°C]	δ [%]
HT heater – 1	660.8	671.2	10.4	1.6
HT heater – 2	670.3	675.5	5.3	0.8
HT heater – 3	688	700.0	12.1	1.7
HT heater – 4	696.2	701.8	5.6	0.8
HT heater	720	719.1	12.9	1.8
Pipe top - 1	717.8	731.8	14.1	1.9
Pipe top - 2	717	731.8	14.9	2.1
Pipe top - 3	713.5	729.8	16.4	2.3
Test section	709.3	730.8	21.6	3.0
Top inlet recuperator	706.8	728.8	22.1	3.1
Central part	447.8	445	2.8	0.6
Outlet Na-air heat exchanger	401.6	386.1	15.5	3.9

For all thermocouples considered, the percentage difference δ obtained is smaller than 4%, underlying the good agreement between the results.

Analysis of the Velocity Field

The flow regime in the pipelines is always turbulent for the entire flow range considered. In the low temperature side, at the moderate flow rate of 125 kg/h and 250°C, the Reynolds number is 10340. In the high temperature heater, at a temperature of 720°C, the Reynolds number varies between 15330 and 19165 for mass flow rates 125-137 kg/h. The velocity streamlines in the shell of the Na-Na recuperator for the case 125 kg/h are displayed in Figure 6. The sodium flow exhibits a meandering character around the two horizontal baffles, considered in order to improve the heat transfer. The turning angles around the baffles increase with the increase in the flow rate due to the elevated kinetic energy. While the flow is turbulent in the inlet and out pipes, in the core of the heat recuperator the maximal sodium velocity ranges between 0.004-0.008 m/s for the sodium flow rates 125-300 kg/s.

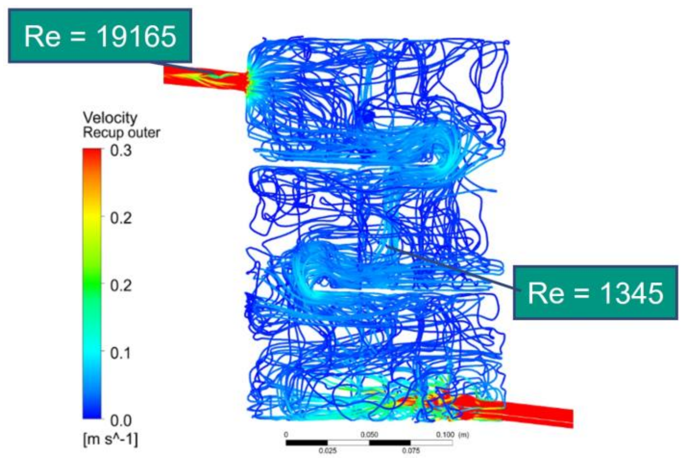

Figure 6 Velocity streamlines in the Na-Na heat recuperator for the case with $\dot{m}$ = 137 kg/h

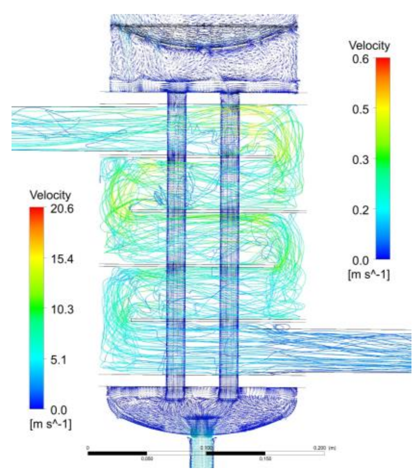

Figure 7 Sodium velocity vectors and air streamlines in the sodium-air heat exchanger

In Figure 7 are displayed the sodium velocity vectors and the air streamlines in the sodium-air heat exchangers. Prior to the entrance in the heat exchanger, a flow distributor is mounted, which ensures a uniform sodium flow distribution. On the air side of the heat exchanger several horizontal baffles are considered, similar to the heat recuperator, in order to ensure a meandering air flow, enhancing therefore the cooling.

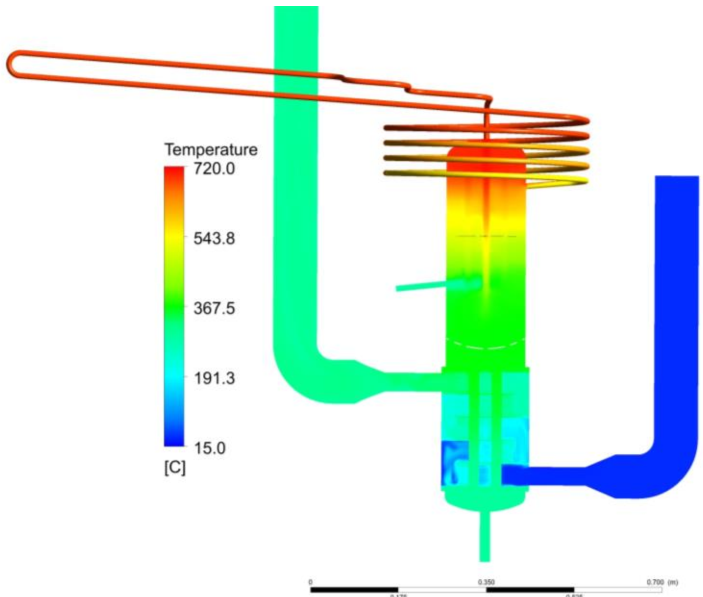

Figure 8 Sodium and air temperature distribution through the model for a sodium flow rate of 125 kg/h at the maximal specified temperature of 720°C

Analysis of the Temperature Field

The temperature field is displayed in mid-plane through the model for a sodium flow rate of 125 kg/h for a test run at the maximal temperature of 720°C, which can be observed at the outlet of the high temperature heater up to the U-type test sample and the top inlet in the sodium-sodium heat recuperator. The experimental data for these flow conditions, as well as the temperatures obtained from the CFD model are compared in Table 2. A strong temperature gradient is obtained through the sodium-sodium heat recuperator and the temperature in the central part, between the heat recuperator and the sodium-air heat exchanger decreases significantly below 550°C. Since this level represents the interface between the upper part made from Inconel and the bottom part made from stainless steel, it is of high importance that the temperature decreases below the mentioned level in order to respect the upper operational limit of the stainless steel.

The turbulent Prandtl number was varied in the range 1.5-2.2, in accordance to the values reported in [10, 11]. Furthermore, the formulation proposed by Aoki [12] was implemented to study the effect of a non-constant Prandtl number and was considered as the reference case:

$$Pr_t^{-1}=0.014\ Re^{0.045}\ Pr^{0.2}\ \{1-\exp[-1/(0.014\ Re^{0.045}\ Pr^{0.2})]\} \qquad (1)$$

The percentage differences obtained at different locations of the model are below 1%. This result suggests that the heat transfer by conduction is the dominant heat transfer mechanism, in the detriment of the convective and turbulent heat transfer. This can be attributed to the rather low velocities and the high thermal conductivity of the sodium. In Table 4 are summarized the temperatures at different locations and their percent difference to the formulation reported by Aoki.

Table 4 Influence of the turbulent Prandtl number on the temperature field for different locations

Location/Pr_t	**$Pr_{t\ Aoki}$** [11]	**Pr_t = 1.5**		**Pr_t = 2.2**	
	[°C]	[°C]	δ [%]	[°C]	δ [%]
Test section	730.8	729.8	0.1	730.8	0
Outlet Na-air HX	386.2	386.5	0.1	387	0.2
Outlet Na-Na recuperator	670.2	669.4	0.1	670.4	0

The temperature profiles in cross-section through the pipe at the outlet of the high temperature heater for different values of the turbulent Prandtl number are displayed in Figure 9. A temperature difference of around 1°C can be observed between the profile for the Aoki formulation and the Pr_t = 1.5. In all cases, the thick thermal boundary layer, specific for low Prandtl number fluids can be noticed.

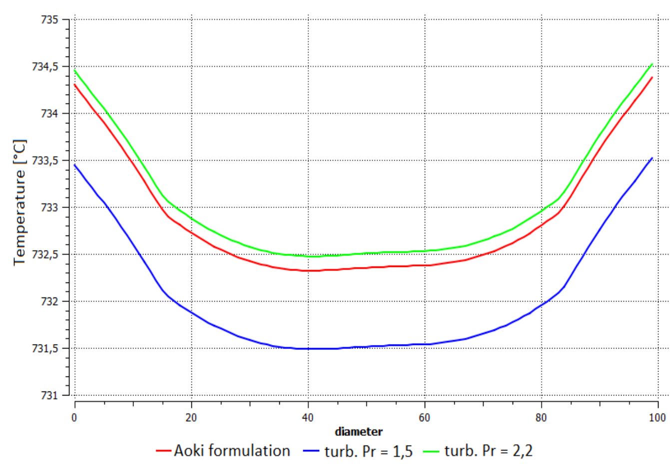

Figure 9 Sodium temperature distribution through the model for a sodium flow rate of 137 kg/h at the maximal specified temperature of 720°C

The Nusselt number was determined for the central tube inside the heat recuperator using the empirical correlation proposed in [13], valid for Pe < 30:

$$Nu = 0.0182\ Pe^{1.74} \qquad (2)$$

to be Nu = 6.28 for a flow rate $\dot{m}$ = 137 kg/h, corresponding to a theoretical heat transfer coefficient α_{th} = 41384.3. A good agreement has been obtained between this coefficient and the heat transfer coefficients determined from the numerical model at different height levels, with the percentage difference being < 3%, as summarized in Table 5.

Table 5 Heat transfer coefficients for different locations along the height of the central pipe in the sodium-sodium heat recuperator

Vertical location [mm]	T_{fl} [°C]	T_{pipe} [°C]	α [W/m^{2}K]	δ [%]
35	543.6	531.8	42 211.9	1.98
110	624.4	612.9	40 330.4	2.58
185	697.4	689.6	41 333.3	0.12

The thermal effectiveness of the sodium-sodium heat recuperator is the ratio of the actual heat transfer to the maximum heat transfer in a counterflow heat exchanger and has been calculated using the following relation [14]:

$$\varepsilon = c_{p\,hot}\,(T_{in\,hot} - T_{out\,hot}) \,/\, c_{p\,min}\,(T_{in\,hot} - T_{in\,cold}) \qquad (3)$$

Considering the experimental values for the temperature and heat capacity the thermal effectiveness has been determined to be 89% for a sodium flow rate of 125 kg/h und 84% for the sodium flow rate 137 kg/h.

CONCLUSION

The present study is focused on the numerical model of the high temperature branch of the SOLTEC-2 sodium facility and on its core component, the sodium-sodium heat recuperator and the sodium-air heat exchanger. Both the sodium flow and the air-cooling flow were considered in the model. The sodium flow is turbulent in the pipeline of the loop, while in the other regions is laminar. A very good agreement has been obtained for the temperature field between the experimental data obtained from the facility and the numerical results, the percentage difference between the results being < 4%. The heat transfer coefficient based on the Nusselt number reported in [13] was compared against the values obtained from the numerical model at three different locations in the central pipe of the sodium-sodium heat recuperator. The percentage difference obtained between them is < 3%.

The variation of the turbulent Prandtl number had no significant difference on the temperature field, underlying the fact that the dominant heat transfer mechanism is by conduction, in the detriment of the convective heat transfer. This aspect is attributed to the high thermal conductivity of the sodium and to the rather low Reynolds numbers.

For the sodium flow rates considered, which are typical values for planned operation, the thermal effectiveness of the sodium-sodium heat recuperator was calculated to vary in the range 84-89%. The use of the heat recuperator reduced significantly the thermal energy required, especially at the steady-state flow regime at high and maximal temperature, and greatly improved the economics of the loop.

For any sodium flow regime, the sodium-air heat exchanger is able to cool sufficiently the sodium below 450-500°C, ensuring therefore a safe operation of the sodium pump.

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