

Desorption characteristics of a lab-scale tube-bundle heat and mass transfer unit

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Abstract

Thermal energy storages tackle the load shift and can balance the availability of supply and demand. Types of storages are sensible, latent and thermo-chemical. The selection of the storage materials – and thus the storage type - is one of the key tasks and depends on the time length of energy storage as well as on power and capacity demand. Because of their high potential energy density and thus their low volume, absorption storages are under investigation. Regarding their heat and mass transfer coefficient for charging and discharging, tube-bundles are an option to form falling films and keep the flexibility of multiuse as absorber, desorber, evaporator and condenser. In this paper, the application of a tube-bundle heat and mass exchangers (HMX) and its characteristics in the charging process step for liquid sorbate i.e. desorption of water (vapor) is presented. The sorbent-sorbate combination is aqueous sodium hydroxide and a concentration difference of 20 wt.% is aimed to reach a high energy storage density. The characterization of different HMX versions in desorption modus are presented in this paper. Even if the best performing HMX versions are not the same in absorption and in desorption modus, it was found that some adaptations could lead to a HMX working decently in both modus.

Keywords: Sorption thermal storage, desorption, tube-bundle, heat and mass transfer.

1. Introduction

Storing energy is essential in energy systems to equalize demand and supply or for power peak cutting. The shift load can be from short term up to long-term of seasons (from summer to winter). With the restriction of low available room – or the prerequisite of using as low volume for the storage unit as possible and as much as needed – thermo-chemical materials are favored. This is because of the potential high volumetric energy storage density (N^oTsoukpoie et al. 2009). In addition, the energy storage is loss less as long the system is not in operation. Absorption based thermal energy storages are widely under research with one focus of long-term i.e. seasonal application (IEA SHC Task 58 ECES Annex 33). One key component of the absorption storage is the power unit, which operates under sub-atmospheric pressure conditions. Tube-bundles used in the power unit as heat and mass exchangers keep the flexibility of multiuse as absorber, desorber, evaporator and condenser (Thome n.d.; Daguene¹-Frick et al. 2015). In the proposed paper we present experimental results of the desorption process step i.e. the charging of the storage with aqueous sodium lye as the sorbent and water vapor as the sorbate.

2. Laboratory test rig and investigated HMX

To assess different kind of HMX, a 1 kW closed sorption thermal energy storage system was engineered and in-house built at SPF (Daguene¹-Frick et al. 2018). This laboratory test rig is shown on Fig. 1. Associated is a CAD view of the facility with description of its main components as well as the fluid flow paths.

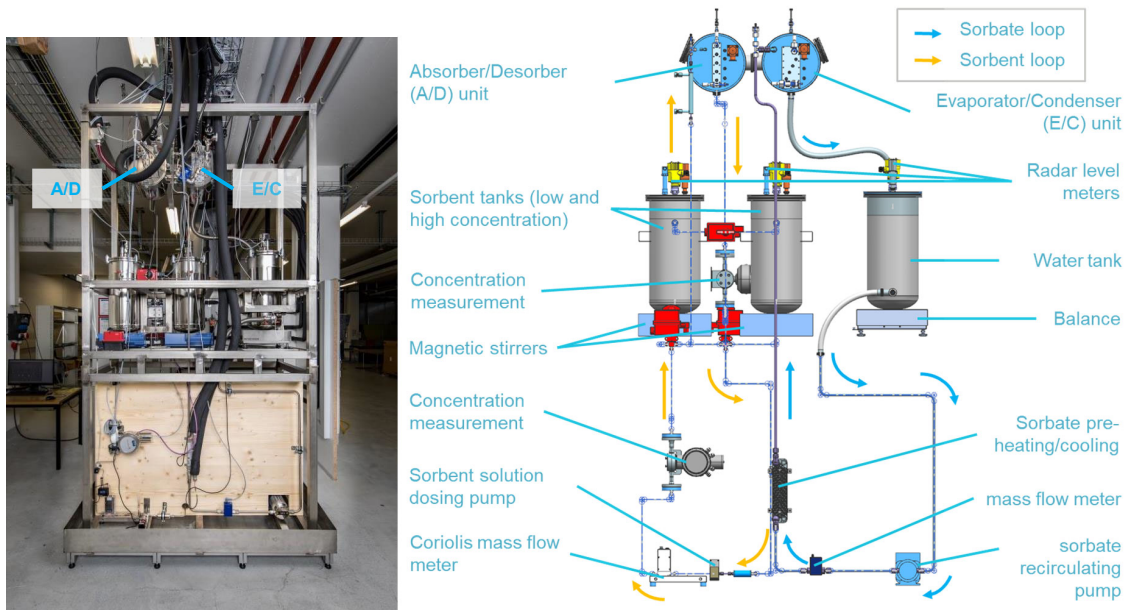


Fig.1: Picture of the laboratory test rig at SPF (left) and associated components description as well as fluid flow paths (CAD view, right).

On Fig. 2, an exploded view, the Absorber/Desorber (A/D) can be distinguished from the Evaporator/Condenser (E/C) HMX. To avoid limitations, this E/C unit was designed large enough, with an active length of the heat and mass exchanger of 300 mm, and to have the A/D as the object of investigation.

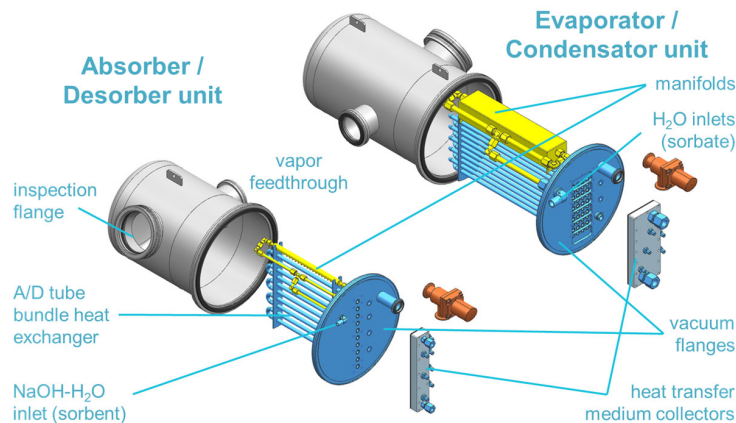


Fig. 2: Detailed view of the A/D and E/C units as well as the smooth heat exchanger tube bundles (exploded CAD view).

For the A/D HMX, different tube designs were used in the experiments, to compare the influence of the enlarged heat exchanger area on the wetting performance. In fact, the wetting behavior of the tube is strongly influenced by the sorbent surface tension, tube surface structure and material. A structured tube surface is favored to increase the interface of the falling liquid sorbent to the sorbate vapor for a high mass transfer rate in the future HMX of the power unit. These HMX serve as absorber and desorber in the lab-scale test rig operating with NaOH-H₂O as sorbent. Tube-bundles with different tube surface structures were retained and implemented in the HMX design as pointed out by Fig. 3. Smooth surface tube bundle (6 and 10 tubes) constitute the reference HMX. These references HMX are compared to a ten-tube textured surface HMX as well as to two six-tube HMX whose tubes are wrapped by a metallic mesh. Two versions of this mesh-wrapped HMX were designed and manufactured (Fig. 3, right).

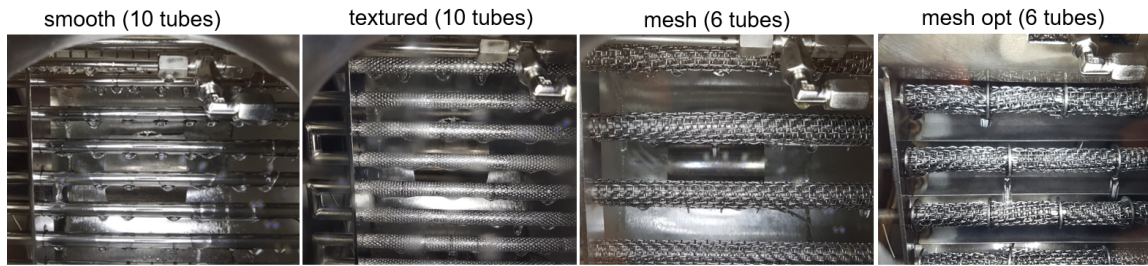


Fig. 3: Tube-bundle types in the power unit of the lab-scale energy storage setup.

In Fig. 4 the HMX second version for optimized absorption process (the limiting process), is shown in detail. Thanks to CCD imaging technologies applied to the former measurement campaigns, wetting aspects were considered for its design:

- Circular washers are placed on the tubes, displaced from one tube row to the next underneath and at equal distances. This arrangement is chosen to enable a good fluid distribution all over the tube bundle. In fact, without washers, a fluid coalescence to liquid sorbent columns were noticed, leading to a bad sorbent distribution on the tubes and thus to lower heat and mass exchanges on the bottom tubes of the HMX.
- Bended washers were placed at the outer (left and right) end of the tubes to avoid sodium hydroxide to flow along the HMX left and right (reinforcement) baffles.
- Deflectors were added to limit the fluid losses during the desorption process. In fact, the metallic mesh enables to enhance the fluid/gas contact area during the absorption process. But during the desorption process it retains the liquid sodium hydroxide close to the tube surface due to the capillarity effects of the mesh – leading to a higher "artificial" hydrostatic pressure. This leads to a higher necessary boiling temperature (vapor pressure) for evaporation on the tube and the triggering of a sparkling phenomenon (local overheating). The sparkling is linked to fluid losses and thus to bad desorption performances.
- The temperature difference (varying between 19 K and 55 K) between the HTF (Heat Transfer Fluid) temperature at the inlet of the absorber ($T_{i,ad}(I)$) and the condenser ($T_{i,ec}(I)$) as well as the sodium lye volume flow rate (36 ml/min and 67 ml/min) were used as the main independent variables.

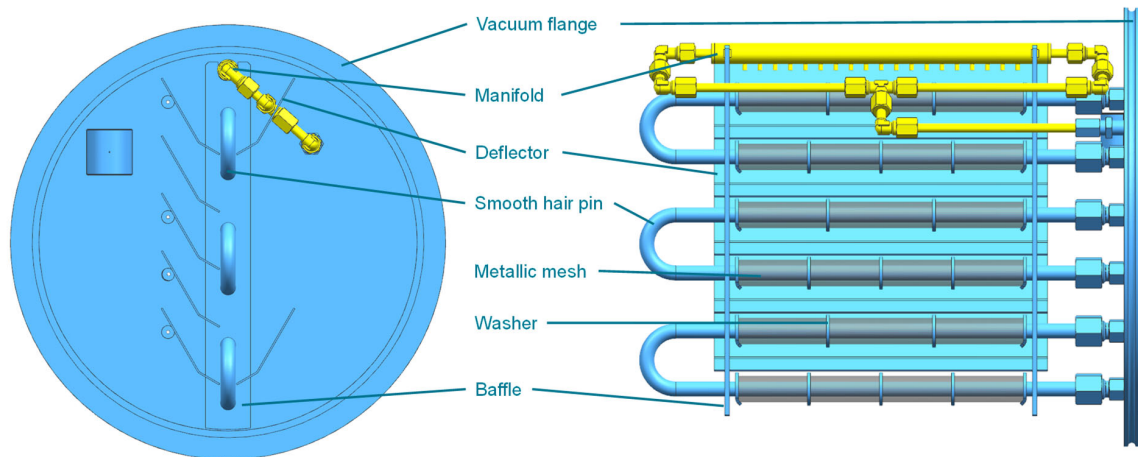


Fig. 4: CAD back- (left) and side- (right) view of the optimized six-tube HMX with washers and deflectors.

For an optical monitoring of the sodium hydroxide flow pattern, three deflectors were removed on the right side of the HMX (Fig. 3, left). For the side view (Fig. 3 right), all deflectors on the right side were hidden from the drawing to simplify the understanding.

3. Results

From a series of measurements that were carried out, results of the desorption process (the storage charging) are presented in this section. For all desorption experiments the sodium hydroxide enters through a manifold, is evenly distributed on the tube bundle and has an initial concentration of 30 wt.% (NaOH in the aqueous lye). During the desorption process, water is evaporated out of the sorbent sodium hydroxide falling along the HMX tube bundle and the concentration is increased. The temperature difference between the A/D and E/C unit constitutes the one independent variable of the desorption process, as it causes a pressure difference - driving force - leading to the vapour transport from the desorber to the condenser unit. The lye volume flow rate was used as the second independent variable.

Fig. 5 depicts the influence of this temperature difference for different HMX geometries on the effective exchanged power Φ (measured on the HTF side, left graph) as well as on the concentration difference between the outlet and the inlet of the desorber (Fig. 4, right). For this measurement campaigns, the inlet HTF temperature of the A/D HMX $T_{iad}(I)$ varies between 43 °C and 80 °C. The other parameters are taken constant: inlet sodium hydroxide concentration $w_{ad}(I) = 30$ wt.%, inlet sodium hydroxide volume flow rate $v_{ead} = 67$ ml/min, heat transfer fluid (HTF) volume flow rate on the desorber side $v_{iad} = 85$ l/h, water recirculation flow rate on the condenser side $v_{ec} = 100$ l/h, HTF volume flow rate on the condenser side $v_{iec} = 200$ l/h and associated inlet temperature $T_{iec}(I) = 25$ °C.

Generally, the power exchanged during the desorption process increases with increasing temperature difference between the (unified) absorber-desorber (A/D) and (unified) evaporator-condenser (E/C) unit. This behaviour is contrary to the results of the absorption measurements where the driving force of the process (the pressure difference) decreases by higher temperature differences.

As a first conclusion, the HMX with textured tubes performs significantly better (in terms of exchanged power as well as concentration difference) than the smooth reference HMX in both desorption and absorption modus. However, with the higher inlet sodium hydroxide volume flow rate of 67 ml/min, a concentration difference of maximum 10 wt.% was reached with the textured tubes and by a temperature difference of 55 K. This is only half of the aimed concentration difference of 20 wt.%. In the desorption modus, the geometries with meshes had a lower performance than the reference HMX. In fact, these meshed geometries were optimised for the absorption modus. However, the performances of the optimised mesh geometry HMX are significantly improved (about 10 %) in comparison to the initial mesh HMX. This effect is attributed to the deflectors, which limit the losses of sodium hydroxide due to the sparkling phenomenon described in former paragraph.

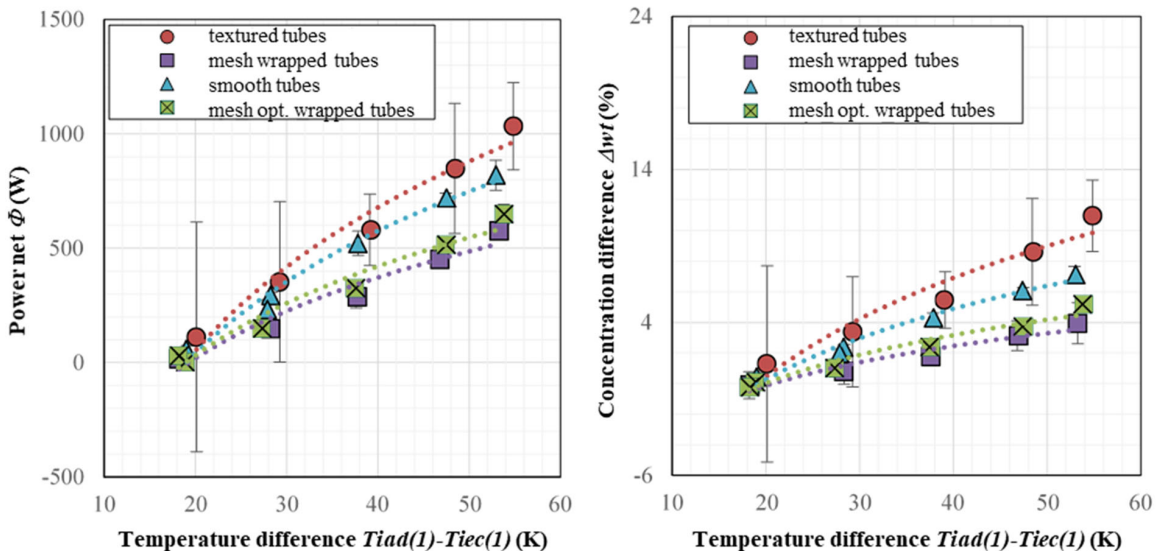


Fig. 5: Power Φ (W) and concentration difference Δwt (%) in function of the temperature difference between the desorber and the condenser unit for different kind of desorber HMX.

Figure 5 shows the influence of the sodium hydroxide volume flow rates (36 compared to 67 ml/min). The desorption power Φ (left) and the absolute difference in sodium lye concentration Δwt (right) are plotted in

function of the desorber to condenser temperature difference (triangle dots for $v_{ead} = 36$ mL/min, square dots for $v_{ead} = 67$ mL/min) for the smooth reference HMX as well as for the optimised mesh HMX. As for the former measurement campaign, the temperature of the cooling circuit (condenser) was kept constant at 25 °C whereas the temperature of the heating circuit (HTF inside the tubes of the desorber) was stepwise increased from 43 °C to 80 °C.

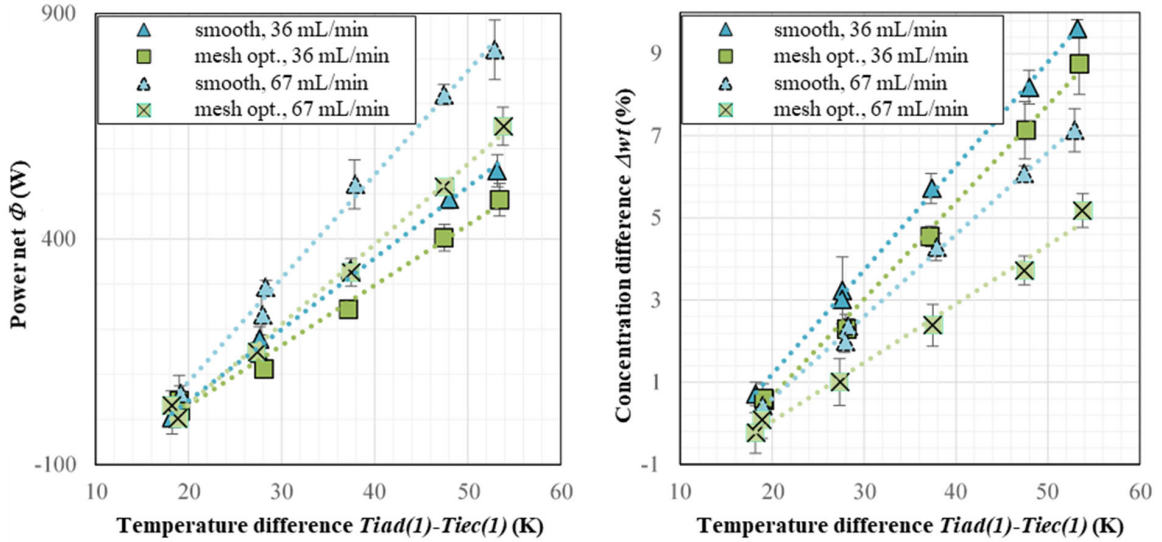


Fig. 6: Power Φ (W) and concentration difference Δw_f (wt.%) in function of the temperature difference between the desorber and the condenser unit for two sodium hydroxide mass flow rates v_{ead} as well as for smooth and optimized desorber HMX.

If the sodium hydroxide volume flow is increased a higher desorption power can be measured. However, at low temperature differences, the desorption power does not increase much with the higher flow as in this case the pressure difference seems to limit the desorption power. Furthermore, for a given temperature difference, a lower sodium hydroxide volume flow rate enables to increase the concentration difference between the inlet and the outlet of the HMX. This enhancement is quite significant for the optimised mesh HMX (more than 50 % of relative improvement) than for the smooth HMX (about 20 % compared to smooth tubes without mesh). In a same way, the sodium hydroxide volume flow has less influence on the optimised mesh HMX than on the smooth one. The explanation for both phenomenon is certainly that the surface wetting as well as the fluid distribution are better (and less dependent on the volume flow rate) for the optimised mesh HMX than for the smooth one.

As a summary of this part, it was shown that, even if the component is optimised for the absorption process, some behaviours concerning the HMX operation are similar in the absorption and in the desorption process (wetting and fluid distribution for example). Furthermore, by taking into account some behaviours specific to the desorption process (sparkling phenomenon for example), the HMX can be optimised to get good performances in both absorption and desorption modes as a compromise.

4. Post processing

In order to figure out the heat losses of such a seasonal storage, it was decided to calculate from the measurements its efficiency in both absorption and desorption modus. In fact, contrary to regular storages, for this kind of storage the losses are not spread over time (the educts are stored and can be maintained indefinitely without losses) but occur during the conversion processes. For the desorption process, the simplified efficiency is calculated as given by eq. 1:

$$\eta_{simplified,desorption} = \frac{\Phi_{net} - \Phi_{DT}}{\Phi_{net}} \quad (\text{eq. 1})$$

with Φ_{net} the net power matching with the power delivered by the desorber to the HTF and Φ_{DT} matching with the power that is lost due to the preheating (temperature rise) of the sodium hydroxide within the A/D HMX. Part of this energy may be gained by adding a recovery heat exchanger to the system (preheating of the sodium hydroxide entering the absorber/desorber).

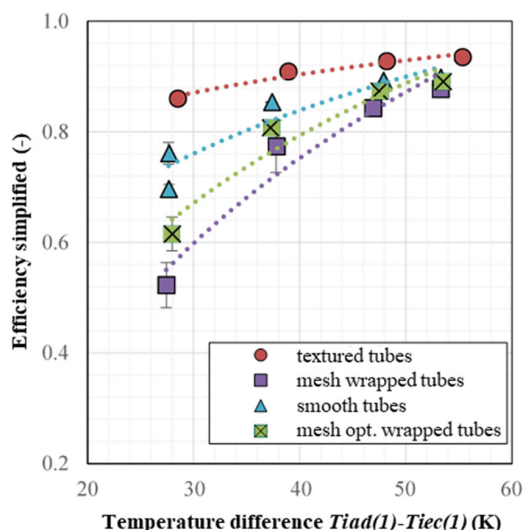


Fig. 7: Efficiency of the desorption process at $v_{ead} = 36$ ml/min of sodium hydroxide volume flow.

Fig. 7 depicts the evolution of the efficiency of the desorption at a sodium hydroxide volume flow rate of 36 mL/min for different temperature differences and various HMX design units. At low temperature differences (inlet HTF temperature of the A/D HMX $T_{iad(I)}$ of about 55 °C), the HMX with textured tubes performs the best followed by the reference HMX with smooth tubes and then the optimized mesh version (itself better than the standard mesh HMX). Nevertheless, at higher temperature (inlet HTF temperature of the A/D HMX $T_{iad(I)}$ higher than 70 °C) - which will also be the working boundary conditions as high concentration differences are pursued as seen in previous section - the differences are narrowing and the efficiency of all HMX is about 90 %.

By combining the efficiency of both absorption and desorption processes, an overall efficiency in the range of 80 % can be expected. This efficiency, already quite high, has surely potential to be increased: additional heat recovery exchanger, better ratio exchanged energy (proportional to the unit volume) vs. heat losses (proportional to the unit surface) for installation larger than 1 kW, possible improvement of the insulation...

5. Conclusion and Outlook

As a conclusion, thermal energy storage tackles a load shifting i.e. the mismatch of energy supply and demand. To fulfil this task, absorption storages are envisaged to be an high energy density alternative to sensible storages. In fact, apart from the operation (conversion process has a given efficiency) absorption storage are loss less as long as they are not in operation. With chosen design, an overall efficiency of at least 80 % can be expected. De facto, tube-bundles for falling film formation keep the simplicity and flexibility to be used in the thermal energy storage power unit, enabling to combine the desorber and the absorber function in a same physical component. A further development and improvement (additive manufacturing for example) is necessary to reach the aimed concentration difference. The combination of the absorption and desorption process steps will enable to save costs and space for the commercial version of the thermochemical heat storage.

6. Acknowledgments

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7. References

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Appendix: Abbreviations and symbols

Table 1: Table of abbreviations and symbols

Quantity	Symbol	Unit
absorber/desorber	<i>A/D</i>	-
charge-coupled device	<i>CCD</i>	-
computer-aided design	<i>CAD</i>	-
concentration difference	Δwt	wt.%
efficiency	η	-
evaporator/condenser	<i>E/C</i>	-
heat and mass exchanger	<i>HMX</i>	-
heat transfer fluid	<i>HTF</i>	-
HTF volume flow rate in the A/D HMX	<i>viad</i>	l/h
inlet HTF temperature of the A/D HMX	$T_{iad}(1)$	°C
inlet HTF temperature of the E/C HMX	$T_{iec}(1)$	°C
inlet sodium hydroxide concentration	$wtad(1)$	wt.%
inlet sodium hydroxide volume flow rate	<i>vead</i>	l/h
net power	Φ_{net}	W
optimised	<i>opt.</i>	-
power	Φ	W
power linked with the fluid preheating	Φ_{DT}	W
temperature difference (independent parameter)	$T_{iad}(1)-T_{iec}(1)$	K
HTF volume flow rate in the E/C HMX	<i>veic</i>	l/h
water recirculation flow rate in the E/C HMX	<i>veec</i>	l/h