CFD MODELING AND VALIDATION OF SODIUM HEAT TRANSFER IN A THERMAL ENERGY STORAGE

Karin Kjellin[1*], Elin Stenmark[2]

[1]Azelio AB, Lindholmsplatsen 1, 41756 Göteborg, Sweden
[2]Sigma Energy & Marine AB, Ekelundsg 1, 411 18 Göteborg, Sweden

ABSTRACT

The increase of cost competitive solar electric power in electrical grids around the world poses a problem when the electricity is abundant mid-day, but naturally declining as the sun sets. Azelio AB offers a solution – the TES.POD - for energy storage which enables 24 hours grid utility energy from solar power. The energy is stored thermally in an aluminium alloy, utilizing phase change. The phase change is the main storage of energy so the temperature is cycled around the solidification temperature of the alloy. It is contained in a vessel surrounded by a sodium jacket, which enables fast and reliable extraction of the heat to power a Stirling engine, producing electricity.

The present paper relates to the CFD simulations of the storage system performance, as well as the consecutive validation in the actual product at Azelios test site in Åmål, Sweden. The CFD model is shown to represent the storage system performance well.

1. CONFIGURATION OF THE TES.POD SYSTEM

2.1 The Case for Thermal Energy Storage Using a Stirling Engine

The intermittent nature of renewable energy sources such as solar and wind points to a rapidly increasing need for energy storage. For the solar energy market, Photovoltaic (PV) technology dominate. Together with BESS (Battery Energy Storage System) the supply of electricity can be extended to 4-6 hours. Longer storage need other, more cost competitive solutions [1]. For this need, Azelio AB has developed the TES.POD, which can produce electricity during the dark hours for 13 hours at continuous operating power.

Whereas the use of TES (Thermal Energy Storage) so far has been primarily connected to large scale CSP (Concentrated Solar Power), the TES.POD can be charged by PV panels by the use of an immersed heater. For discharge of energy, Azelio uses its Stirling engine with which the company has accumulated more than 2 000 000 operating hours at landfill sites and in solar parks. The advantages of the Stirling engine compared to steam turbine energy conversion are many. Firstly, a steam turbine based power block benefits from size, i.e. the larger turbine the better efficiency. This drives the need for large facilities, typically >100MW, to be cost competitive. With high energy output comes high cost of the connected infrastructure, since the facilities are often located far from the end electricity consumers. The Stirling engine by contrast has high efficiency even for smaller systems – the heat-to-electricity efficiency is around 30% for Azelio's Stirling engine (which is rated at 13kW electric power). This opens for a modular solution, able to produce cost competitive around-the-clock renewable energy in facilities between 0.5-20MW, which can be installed near the end user in a distributed manner. Secondly, a steam turbine based power block is highly vulnerable to failures, forcing the entire facility to be closed down in case of faults or even planned maintenance. For a modular solution, separate units can be serviced (or repaired) one at a time in a rolling schedule without affecting the overall facility energy output. Lastly, the Stirling engine does not require process water which is a benefit in many geographical locations.

*Corresponding Author: karin.kjellin@azelio.com

2.2 Choice of Storage Material

In designing the system, the requirements for storage material were high energy density, a suitable working temperature range, and high availability – the latter criteria indicating also favourable pricing.

PCM’s (Phase Changing Materials) in general fulfil the first two criteria. Utilizing phase change energy (compared to utilizing only a change in temperature, known as sensible heat) inherently leads to a higher energy density in any given material. As for temperature, a PCM naturally releases its energy at a well defined, narrow temperature span which is favourable for the Stirling Engine. The task was hence focused to find a well suited PCM for the TES.POD.

In general, a higher melting point correlates with higher melting enthalphy (see [2]), and together with good cost structure, salts were considered an interesting alternative. However, the low thermal conductivity of salts makes heat transfer from the material difficult to achieve, and hence likely leads to lower temperature output to the Stirling engine, which in turn gives lower system efficiency. In some cases, the high melting point also rules out the use of common construction materials, leading to a more expensive end product. Designed storage materials, such as MGA (Miscibility Gap Alloys) and thermochemical storage in nano-coated salt, are highly interesting but at this point lack the Technology Readiness Level and cost competitiveness that are required for the product.

Azelio’s choice of PCM is an eutectic mixture of aluminium and silicon. The material does not degrade over time if kept in an inert environment, it is abundantly available and at a low cost. Using recycled material and producing it with renewable electricity, it is also a sustainable choice. A similar system (eutectic AlSi alloy together with Stirling engine) was proposed by Rea et al in [3].

2. CFD MODEL OF THERMAL STORAGE

4.1 Functional Description of TES.POD Energy Discharge

Figure 1: a) Discharge HTF loop overview b) CFD model including storage material, steel vessel, discharge HTF jacket, pump and simplified heat exchanger.

Figure 1a shows the thermal storage and discharge HTF (Heat Transfer Fluid) pipes, excluding insulation. The storage is surrounded by a jacket of HTF, which is liquid sodium. The sodium is pumped by the pump closest in view, to the Stirling engine heat exchanger which is the yellow part on the left. The sodium then returns to the jacket and flows around the storage, back to the pump as shown with the white arrow. Figure 1b shows the corresponding CFD model.

4.2 Simulation process outline

The discharge process of the thermal system is challenging to simulate due to the long physical time frame (13hrs) combined with flow of sodium and a quite complex geometry. The simulation resource at the time of model development was an Intel(R) Xeon(R) Gold 6148 CPU @ 2.40GHz cluster of 160 cores, and the aim was to simulate the discharge process with a reasonable degree of accuracy during one week. The process was outlined as follows:

1) Time resolved RANS simulation of the sodium system together with the thermal storage for a short time, to achieve a stable flow field in the sodium system. The velocities are fixed to zero for the aluminum alloy domain.

2) Freezing of all equations except the energy equation, and running the full simulation at a high (~1s) time step.

This process is arrived at with the assumption that a) forced convection is dominating the sodium flow field, natural convection does not have to be taken into account and b) the flow field inside the thermal storage (the aluminium alloy) is not of importance to the systems performance and is set to zero. The last assumption has been investigated separately.

The sodium circuit is simulated as a closed loop, where the pump impeller is replaced with a fan interface which is tuned to give design flow. The heat exchanger draws a constant heat flux from the system. Known heat losses from the storage are added to the outer surfaces - these are small in comparison to the heat drawn by the Stirling engine.

The simulation is started with an initial temperature of 578°C, i.e. just above the solidification temperature.

The sodium system as well as the thermal storage itself are modelled using ANSA for meshing, and ANSYS Fluent v18.2 for the simulations. The solidification model in Fluent is used for phase change in the PCM domain.

4.3 Mesh Considerations

Due to the long physical time frame of the transient simulation, it is also of importance to keep the cell count as low as possible. A detail of the mesh is seen in Figure 2. As can be seen, the mesh is very coarse (10 mm) in the larger part of the PCM, which is reasonable since there is practically no flow in this region. The temperature solution together with the solidification model still gives a satisfying simulation resolution. In the HTF region, the wall boundary layer is resolved using prismatic cells. This is a practical consideration to ensure enough cells across the thickness of the jacket. Since the HTF is Sodium, the Pr number is low and hence the thermal boundary layer is thick compared to the viscous boundary layer, corresponding to a requirement of a y+ of 17 which is fulfilled in the larger part of this region for the design flow.

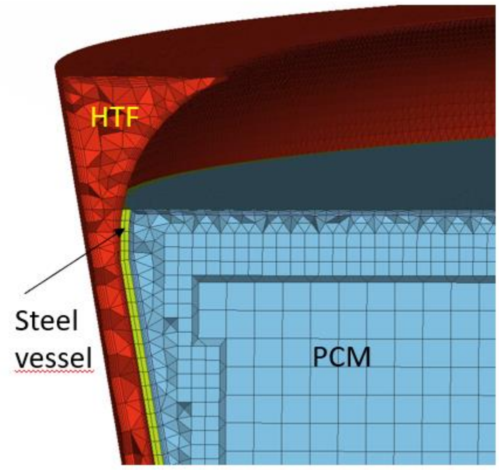

Figure 2: Mesh detail from upper part of the storage vessel.

3. RESULTS

5.1 CFD results

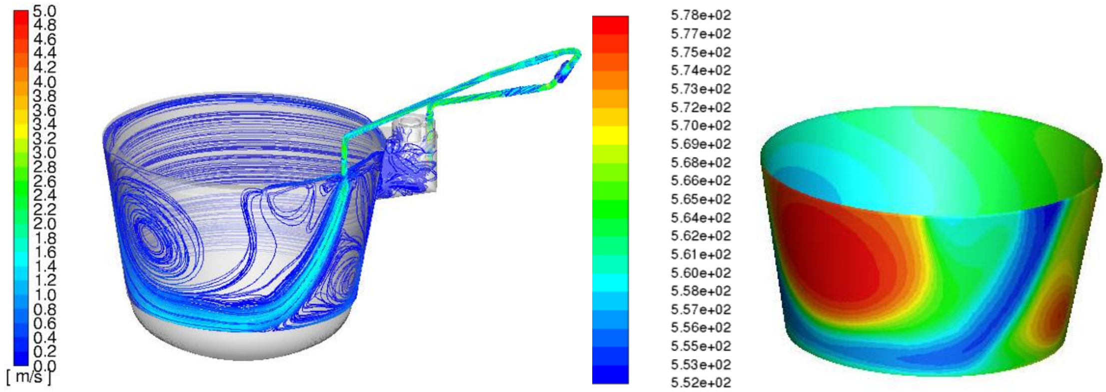

Figure 3: **a)** Sodium flow field at design flow, 2l/s. **b)** Temperature [C] at 23 000s.

Figure 4a-c: Iso-surface of liquid fraction showing the solidification front at t=5000s, 30 000s and 57 000s.

Figure 3a shows the sodium flow field, which is kept constant throughout the simulation as discussed above. **Figure 3**b shows the resulting temperature on the PCM surface at 23 000s. The effect of the sodium flow field is clearly visible in the resulting temperature (and heat flux) fields. The recirculation areas to the right and left of the incoming flow has higher temperature throughout the discharge cycle.

Figure 4a-c shows the resulting solidification front. In a) the high temperature recirculation zone is still visible to the right of the return pipe, where solidification has not yet started after 5000s. Since the discharge jacket does not extend all the way down to the bottom of the vessel, liquid PCM is left last at the bottom ensuring good thermal contact to the vessel wall during the subsequent charging of the system. (The charging cycle is not in the scope for the present article.)

5.2 Comparison to measured data

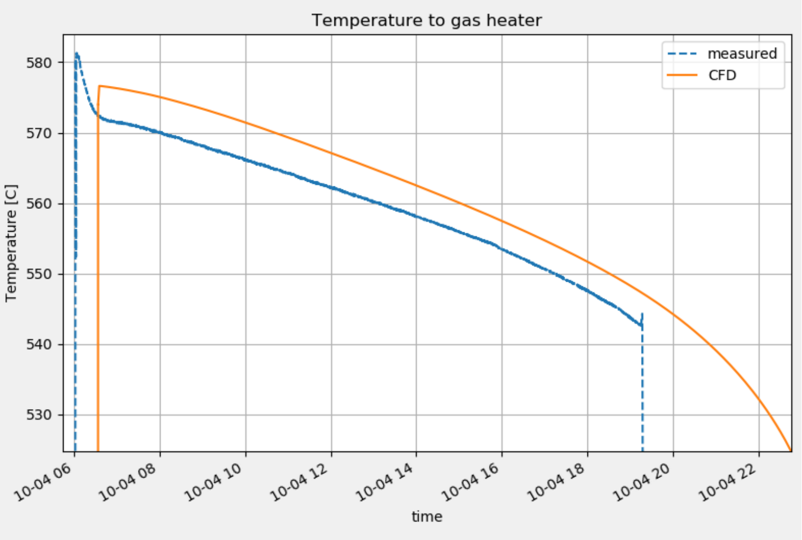

Figure 5: Sodium temperature, CFD results vs measured values. Time scale is from 6 AM to 10PM.

Figure 5a shows the simulated sodium temperature into the gas heater (Stirling engine heat exchanger) together with the temperature measured over 13 hours, a typical discharge cycle for the TES.POD. The equivalent temperature was measured with temperature sensors in dip-tubes extending into the sodium flow. As can be seen, the measurement starts at above 580°C, where some overheating of the thermal storage is extracted from the system. The curve steeps sharply to the point where the phase change of AlSi starts, which is also the start of the CFD simulation.

The CFD simulation predicts a similar curve as the measurement shows, but 5°C higher. The probable reason for this is that the AlSi was simulated as an eutectic composition for simplicity. This means that its solidification and melting temperatures coincide, in this case at 577°C. It is known, however, that the exact commercial alloy that is used is not fully eutectic due to impurities. Separate simulations of the non-eutectic mixture shows that the expected gas heater temperature is a few degrees lower, which would explain the deviation between simulation and measurement in this case.

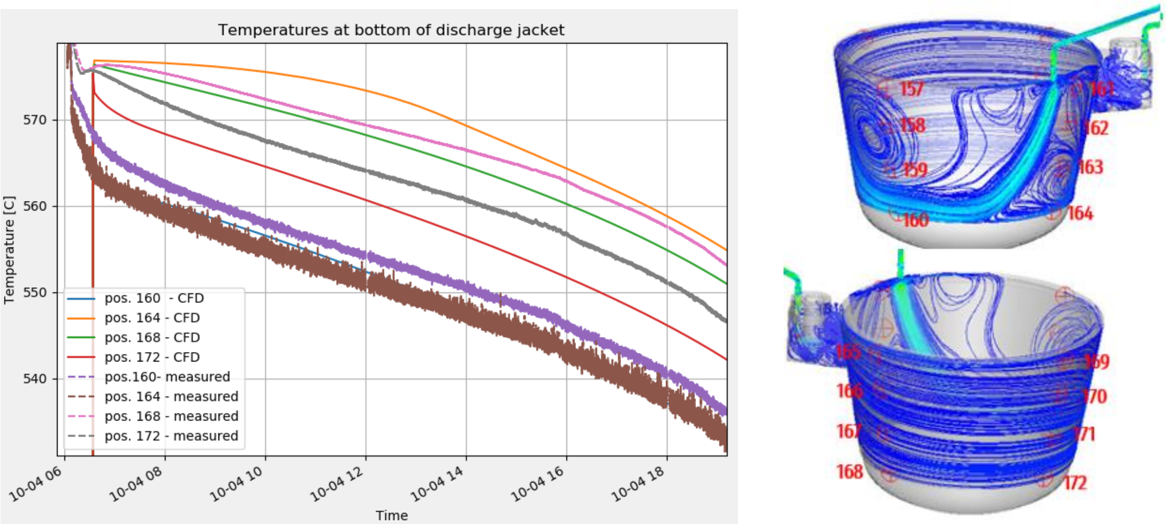

Figure 6: Temperature measurements at the bottom of the discharge jacket vs simulated data. Locations of sensors on storage tank, shown with streamlines.

Figure 6 shows measured temperatures at the bottom and outside of the discharge jacket, together with the equivalent values from CFD. The sensor positions are indicated to the right. The agreement between simulation and measurement is generally very good. What stands out is some locations such as pos. 164, where there are flow recirculation zones. These locations tend to be a lot warmer in CFD, indicating that the "frozen" flow field is overpredicting the effect of such zones on limiting the heat transfer. The same is true for instance at pos. 158 and 159 (not shown here). The actual flow field is likely to fluctuate, thus increasing heat transfer and over time lowering the jacket temperatures in these locations. This may also contribute to the overall CFD result (**Figure 5**) being slightly warmer than the measured data.

4. CONCLUSIONS

The CFD model represents Azelio's thermal energy system performance well and will be used for further evaluations of the system, for instance for future design modifications.

REFERENCES

[1] Long Duration Energy Storage Council, *Net-zero power – Long duration energy storage for a renewable grid*, (2021)

[2] H. Mehling & L. F. Cabeza, *Heat and Cold Storage with PCM*, Springer Verlag (2008), Berlin Heidelberg

[3] J. Rea et. al., "Performance modeling and techno-economic analysis of a modular concentrated solar power tower with latent heat storage", Applied Energy 217 (2018)