Preliminary Simulation of the Sodium Thermal Energy Storage Verification Test Facility with Modelica

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1. Introduction

The growing market share of renewables leads to a great challenge for the electric grid to deal with the innate intermittency of such energy sources. The most known solution is energy storage systems (ESS) in diverse forms, where their working principles are as simple as to store energy that can be drawn out with ease or that can be transformed into electricity. Among others, the thermal energy storage (TES) systems are basically heat reservoirs that can hold heat for a while with a limited energy loss, and that distribute the stored energy in response to demands.

Furthermore, the worldwide consensus on reducing carbon emissions from the energy sector accelerates this market share transition and imposes stricter regulations to rule out fossil fuel plants. On the contrary, the near-zero carbon footprint of nuclear powerplants makes them competitive as can be seen in the EU taxonomy which recently categorized nuclear power as clean energy. Nuclear-renewable hybrid energy systems (NRHES), which encompass a number of different arrangements defined by the degree of coupling between nuclear and renewables, are novel attempts to fulfill the current imperative to the best.

In this regard, we are now studying the application of sodium as an alternative heat storage medium for a TES system as a subsystem or a subcomponent in an NRHES. Its high boiling point contributes to a possibility of higher temperature application and material compatibility assures a cost-effective solution in comparison to conventional TES systems using molten salts.

We are considering a sodium TES verification test facility to experimentally investigate its applicability [1]. The test facility also aims to establish vast operating datasets with which optimal operational scenarios and requirements can be drawn out in conjunction with nuclear and renewable energy sources in the near future. In support of this experimental work, this study focuses on developing models to be used for the simulation of the test facility based on the Modelica language. The simulation model can help design the facility from early stages by providing expected behaviors under specific design requirements, and finally contribute to minimize any kinds of trial errors. Furthermore, the simulation data are expected to be compared to test results and this comparison will be utilized to scale up from lab-scale to pilot-scale.

2. Model development and verification

2.1. Problem definition

A sodium TES is thought to be a two-tank system of two large vessels; one of which stores hot liquid sodium while the other contains cold sodium. Compared to molten salts, sodium has high thermal conductivity which makes a one-tank thermocline system inefficient and impractical. Another major gain from the physical separation of hot and cold tanks is system simplification and reliability in terms of system control.

The test facility we are considering merely consists of two large vessels of high- and low-temperature TES tanks operating at around 700 °C and 200 °C, respectively, pumps that regulate sodium flows, several heaters and heat exchangers representing heat sources and demands, a piping network connecting these components, and auxiliary fluid systems supporting the system integrity and maneuverability [1]. The simulation of the facility thus can be conducted by splitting the components of facility into several simple models defined by physical relations.

2.2. Development environment

Modelica is an open-source, high-level language based on C/C++ specialized in solving physical phenomena mathematically described by several ordinary differential equations and algebraic equations (DAEs) [2]. One of the distinct features of Modelica is that it enables describing physical systems in human-readable DAEs with little adaptation to corresponding machine-readable forms. The Modelica compiler does a quick check if a model is well built in terms of balance between the number of parameters and that of equations. This process helps users adapt to the language without a deep understanding on computer sciences and to run analyses on complex physical systems taking advantage of fast computational time owing to the C/C++ architecture.

Another important strength of the language is its object-oriented programming through inheritance and redeclaration. These features allow a user to reuse or to slightly modify pre-developed components. The slight modification also includes joining of some low-level, low-scale components to build a large-scale one, by setting up linking relationships among them.

Modelica provides a lot of physical models and thermophysical property libraries which can also be expanded by inheritance and redeclaration in its base library. Currently, the language is distributed as Version 3.2.3 and 4.0.0, with the latter being the officially managed while the former being treated as legacy in support of users needing the old version. Even though their functionalities and capabilities are almost identical, the two versions do not share their namespaces and cannot be read without manual migration. In this study, the preliminary models are developed under Version 3.2.3 due to dependence on an outdated third-party library, while it will be further migrated to Version 4.0.0 in consideration of code stability.

The compilation of an input deck originally written in Modelica to C/C++ can be done by several compilers including commercial compilers such as Dymola and JModelica, and an open-source compiler OpenModelica, also developed by the Modelica Association. The models thus developed in this study are compiled by OpenModelica, Version 1.19.0.

2.3. `NaTES` *package*

Modelica provides a special variable type `package`, which is equivalent to a library in other languages, so that several models and components as a whole can be hierarchically managed with prescribed dependences. The models developed in this study are wrapped in the `NaTES` package as Figure 1 which shows its up-to-date constituent submodels at the moment. The package contains not only the model `ExpansionTank` that is elaborated in Section 2.4 but a number of partial models, icons and graphically illustrative parts, and examples which serve as specific conditions set up for case studies given in Section 3. The package and its submodels will be updated appropriately.

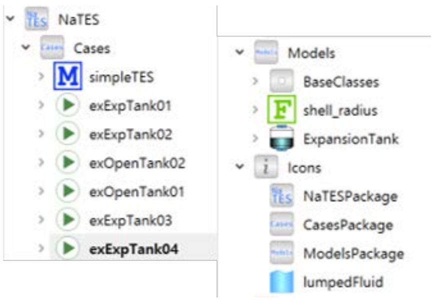

Figure 1. Tree-view of `NaTES` package.

2.4. `ExpansionTank` *model*

Most of the Modelica models aim to analyze the temporal change of variables in volumes where they are described by pointwise or one-dimensional formulations. In this respect, the integral behavior of a system is of a higher value in practical Modelica simulations than analyzing the distribution and local changes of physical properties in a specific component through domain discretization. The TES vessels in the test facility also went through this simplification seen as a point model without considering the temperature and velocity distributions internally and locally. Even though the scale of the high- and low-temperature TES vessels in the test facility is up to around seven metric tons (7000 kg) in terms of sodium capacity [3], this simplification would be suitable owing to the high thermal conductivity which results in a rather uniform temperature distribution. In addition, small temperature perturbations can presumably be suppressed well due to the fact that large sodium flows only take place near the sodium inlets and outlets of the TES vessels.

The sodium free surface levels are anticipated to be affected by sodium net influx, sodium temperature change, and dynamic change of cover gas inventory. It indicates that the cover gas which takes up the upper part of the vessel and its physical behavior as well as sodium flow should be treated separately so that the levels can be tracked properly as the two fluids are almost immiscible. There is no model to equivalently simulate such condition in existing Modelica library and thus we have built a specific model for the TES vessels and named it as `ExpansionTank` by considering the issues listed and by taking advantage of the object-oriented programming nature of Modelica through revisions in terms of inheritance and redeclaration. Figure 2 depicts the whole process of model development.

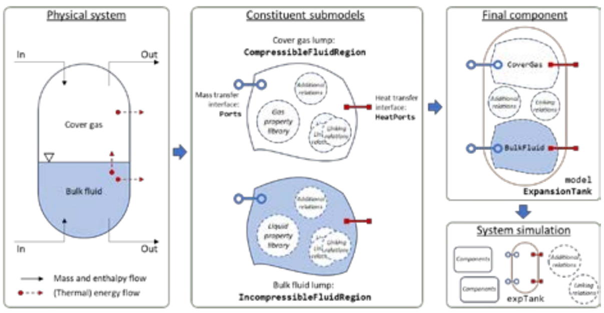

Figure 2. Schematic representation of `ExpansionTank` model development.

2.5. Verification of the ExpansionTank model

The `ExpansionTank` model developed in Section 2.4 was numerically verified through code-to-code benchmarks in comparison with generic models provided in the Modelica base library. Boundary conditions were also set so that those compared were physically equivalent to the developed model. The verification was carried out in view of hydrostatics and heat transfer one by one.

2.5.1. Hydrostatics verification

The benchmark target is `OpenTank` of the base library (`Modelica.Fluid.Vessels.OpenTank`), in which its lid is open to its surroundings. Thus, an environment model (`Modelica.Fluid.System`) should also be included for the whole system can be run. It requires that the cover gas volume of `ExpansionTank` needs to be connected to a boundary condition by which the cover gas pressure is maintained at a specified pressure with no fluid transfer being involved. For both systems, the free surface levels are monitored during the working fluids are fed with a constant flow rate into the tanks from the bottom. The verification problem setup for the two systems is graphically illustrated in Figure 3.

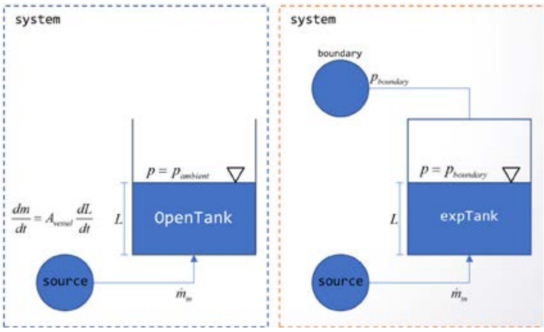

Figure 3. Problem setup for hydrostatics verification using `OpenTank` (left) and `ExpansionTank` (right).

The solutions shown in Figure 4 obtained by imposing equivalent boundary conditions to each of the systems indicate `ExpansionTank` behaves correctly.

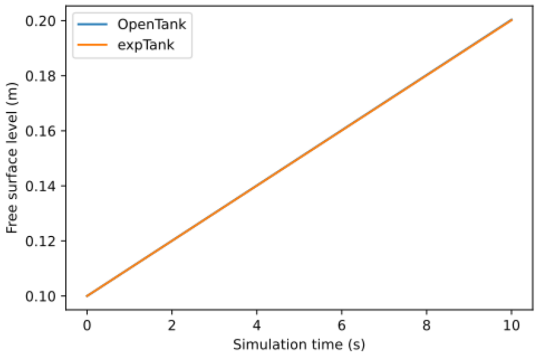

Figure 4. Free surface levels simulated by `OpenTank` and `ExpansionTank` (abbreviated as expTank) under a constant flow.

2.5.2. Heat transfer verification

Likewise in Section 2.5.1, the benchmark target for the heat transfer model verification is `OpenTank`, which has an option to be treated as a thin vessel where heat loss through the inner surface in contact with the fluid can be modelled as if there exists a zero-thickness wall. The heat loss model in `ExpansionTank` has two separate heat transfer models similar to that of `OpenTank` since two media take up the internal volume of vessel exclusively. The problem setup for the two systems is depicted in Figure 5.

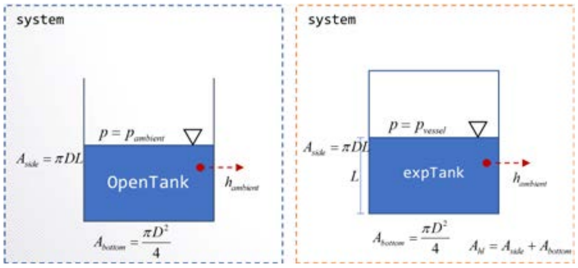

Figure 5. Problem setup for heat transfer verification using `OpenTank` (left) and `ExpansionTank` (right).

In addition, it contains an optional heat loss model from the working fluid to the cover gas, through the free surface as if the working fluid is a solid wall, although the option was made inactive here. Given these differences, physical equivalence is achieved by selectively activating the heat loss model through the walls touched by the working fluids in the two systems. With selected cases where the environment is at 20 ℃ with the convective heat transfer coefficient of surrounding air being 5, 10, and 20 W/m^2 K, we obtained simulations results illustrated in Figure 6, indicating the heat loss model implemented in `ExpansionTank` works as defined.

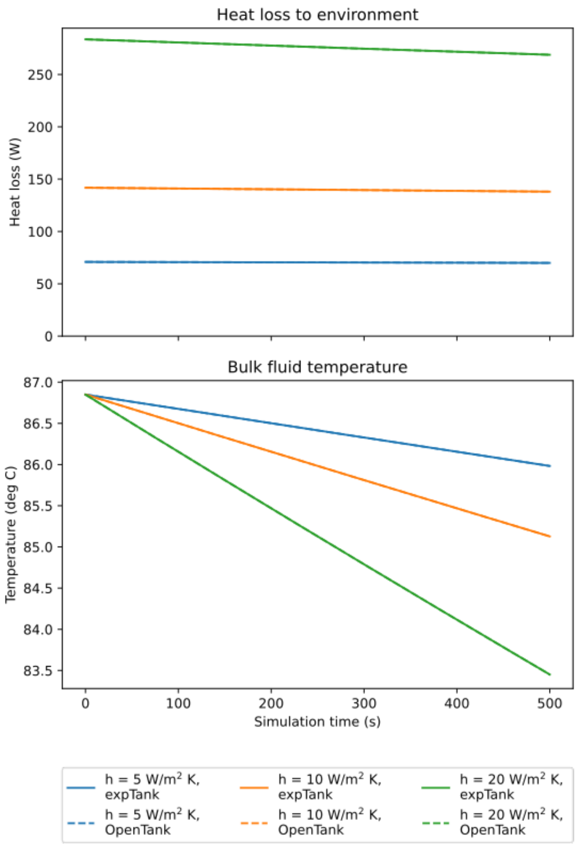

Figure 6. Heat loss to the environments (top) and working fluid temperature change (bottom) simulated with `OpenTank` and `ExpansionTank` (abbreviated as expTank).

3. Preliminary simulations of the sodium TES verification test facility

Several case studies were conducted by postulating practical conditions in terms of test facility operation using `ExpansionTank`.

3.1. Working fluid transfer by cover gas purging

Working fluid can be transferred by cover gas pressure as a result of charging it into a specific segment of a fluid system. This section summarizes the systematic behavior of a hypothetical system under such condition. As shown in Figure 7, the analytic system is set up with the air temperature and pressure at 20 ℃ and 1 bar, respectively, where a reservoir and a closed vessel modeled with `ExpansionTank` have a 0.5-m level difference and the cross section of the reservoir doubles that of the closed vessel. The bottom ends of the two vessels are connected with a simple, frictionless conduit with no form loss being involved, while the cover gas region is set up with a constant mass-transfer boundary condition of 0.001 kg/s, being transferred to the region from one second (1 s) after the simulation starts. The initial free surface levels are given to be 0.1 m.

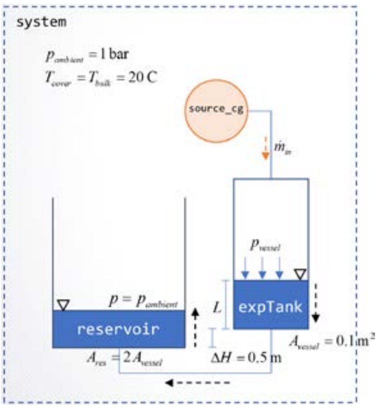

Figure 7. Problem setup for a working fluid discharge system by cover gas purging.

Figure 8 shows the analysis results on the working fluid transferred by cover gas purging. As the cover gas is regulated from one second after the start, the free surface level in the closed vessel falls down while the free space is covered by the cover gas purged. Since the cross section of the open vessel is twice larger than that of the closed vessel, its absolute level rise is exactly half. What is also notable here is that although it lasts in a short period of time within a second from the beginning, the free surface levels equalize passively by their static heads. As a result, the cover gas pressure in the closed vessel decreases and its temperature also falls due to its adiabatic expansion. The temperature recovers since the purged gas is at 20 ℃.

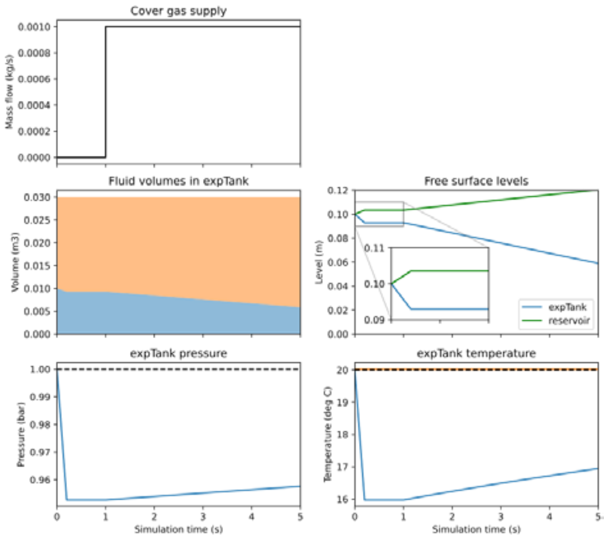

Figure 8. System analysis results on the working fluid transfer by cover gas purging.

3.2. Automatic cover gas pressure control at a specific set value

Even though the TES verification test facility has not yet been built, it is trivial that the facility shall be able to control cover gas influx and outflux according to experimentalists' discretion and even without their frequent manual intervention. As explained in Section 2.4, the most critical reason that we split the active volume of `ExpansionTank` was eventually to make the operation logics of the facility successfully captured and simulated. Hence, this case study runs a system that actively regulates the cover gas pressure at a given pressure with respect to the changes in controlled parameters of a TES vessel.

Figure 9 depicts the analytic system setup by means of the `annotate` feature of OpenModelica. The closed vessel shown in the figure (`expTank`) is charged by a fixed flow source operated on-and-off, prescribed by a 10-second cycle where the source runs at 0.25 kg/s of net fluid flow for five seconds (5 s) from the beginning and then stops for the other five seconds. The cover gas region is connected to a feedline at 5 bar while also ventilated through an additional line at 0.5 bar. Between these boundaries exist two ideal valves, `valveFeed` and `valveBleed`, representing a feed valve and ventilation valve respectively, regulating the cover gas pressure in accordance to their operational logics. These two valves are assumed to be governed by a stepwise hysteresis commonly such that their open/close statuses are flipped reversely when the cover gas pressure is measured to differ by ±5% from its set value of 1 bar. In other words, if the pressure is measured to be 1.05 bar, then the `valveBleed` is opened to release pressure, while `valveFeed` is opened if it gets to 0.95 bar.

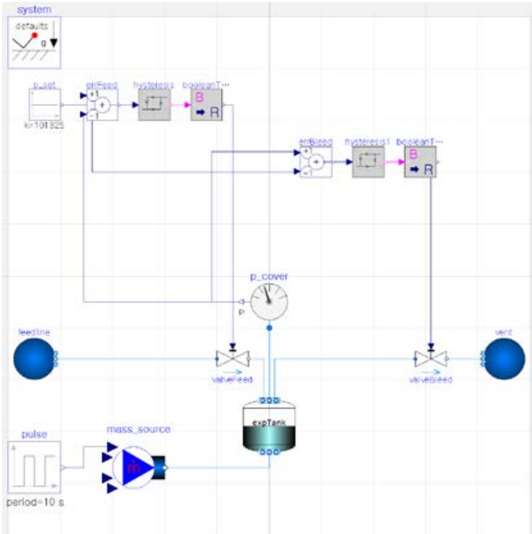

Figure 9. Problem setup for a simple system where the automatic control of cover gas pressure is applied.

Figure 10 illustrates the analysis results on the automatic cover gas pressure control. The cyclic operation of the fixed flow source gives rise to the stepwise free surface level rise, which in turn affects the cover gas pressure and simultaneously triggers the valves to be maneuvered to control the pressure within the prescribed control range. At the same time, one can see that the heat loss model through the free surface, omitted in the benchmark given in Section 2.5.2, contributes to the temperature rise in cover gas since the working fluid underneath is at 87 °C. Note that this temperature rise is also thermodynamically given by the cover gas pressure rise when it is filled from the feedline. We expect that the operational procedures of the facility can also be drawn out through these case studies and the simulation results can also be more realistic with actual valve control logics involved once the facility is up and running.

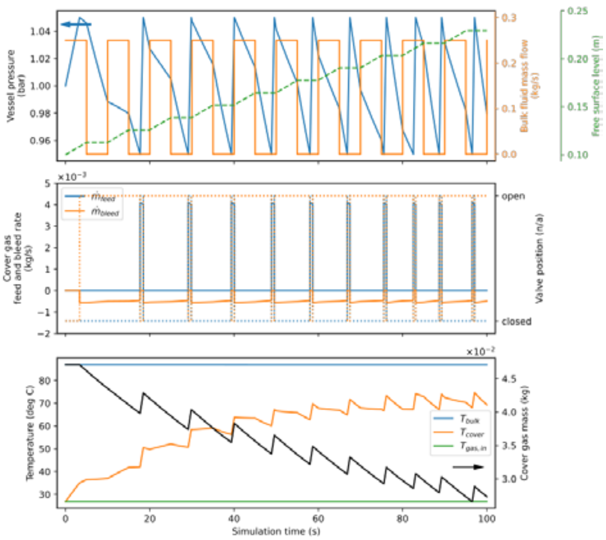

Figure 10. System analysis results on the automatic cover gas pressure control.

4. Summary and future work

We have established a simulation capability in Modelica specific to the sodium TES verification test facility, which is scheduled to start its construction in this year, to obtain its operational logics and to analyze the experimental results. Considering the components in the setup, we have concluded that a specific model for the high- and low-temperature TES vessels is necessary since the models in the base Modelica library are not suitable for simulating the dynamic change of cover gas inventory. Thus, we developed a new model `ExpansionTank` and a package `NaTES` to track down its update. A few code-to-code benchmarks covering hydrostatics and heat transfer were conducted to verify that its behavior is correctly modeled as defined, with similar models included in the base library by composing physically equivalent problem setups. In addition to the verification, we ran several preliminary case studies to analyze the behaviors of generic setups that can be directly thought to be similar to the test facility.

As the library and model are under development, we identify some model updates to make the model more reliable and realistic. The free surface levels would not be given as a linear relation to the sodium volumes filling up the tanks as they are finished with elliptic caps [1], indicating that a nonlinear relation should be set to obtain the sodium volumes from the measured free surface level data reliably. The active volume control of cover gas should be implemented with actual component logics as well.

ACKNOWLEDGMENTS

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