Development Of Training Simulator Software For Molten Salt Parabolic Trough Test Platform

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Abstract. Operators of a solar-thermal power plant bear a high responsibility as they are in charge of the plant integrity, the safety of staff and optimal performance. At the same time, the complexity of such plants is very high. Thus, skilled operators are needed to understand what they do and, especially, how to react in non-standard plant conditions. Training the operators for these situations is very important for trouble-free operation. Those items become particularly crucial for testing of parabolic trough plants with molten salt as working fluid, as they inherit the danger of HTF freezing at normal ambient conditions. DLR developed a training simulation software as a platform to train the operators in dealing with various scenarios and test automation concepts for plant control for the test facility in the HPS2 project. The simulator software features a detailed model for transient simulation of the solar field based on DLR's Virtual Solar Field (VSF), a simulator management system and a human-machine interface (HMI). VSF communicates via a standard TCP/IP interface with the simulator management. The plant model features detailed modelling of the hydraulic network and storage system, alarm functions and control logics derived from the functionality of the test plant. The HMI is designed according to the real process control software. Simulations with measured weather data validated the correct behavior of the physical models. To understand the behavior of the plant, the plant model can be completely manually operated. Various weather scenarios can be loaded to show difficulties of transient situations, like a sudden direct normal irradiation (DNI) rise or drop. This enables the trainer to show real operation scenarios of the molten salt plant during the training course without endangering the test facility.

INTRODUCTION

Parabolic trough concentrated solar power plants are promising candidates to address the need for dispatchable electric energy in future markets. They are capable of separating electricity generation and availability of solar irradiation via thermal storage concepts at low costs compared to battery systems. The next step in technology is the switch from thermal oil to direct use of molten salt as the heat transfer fluid for the solar field. As the process for such plants differs in many aspects from the conventional parabolic trough plants with thermal oil as the heat transfer fluid, new challenges arise for control systems and the operational team. Within the HPS2 project, the German Aerospace Centre (DLR) together with various research and industry partners builds up a test plant for research on line-focusing collectors with molten salt as the heat transfer fluid (HTF) in Évora, Portugal [1]. The Test loop will be the basis of the Évora Molten Salt Platform (EMSP), which will house future research projects [2]. During the project, a training concept needs to be developed to give all candidates of the operating team, which may come from various backgrounds, the knowledge how to safely operate the test facility and how to react in emergency situations. As central part of this training, a simulator software is being developed at DLR. The idea behind the simulator is to train the operating team on real weather scenarios to understand the behavior of the molten salt system before commissioning the test facility.

SIMULATOR CONCEPT

Requirements

The basis of the simulator is the plant design developed in the HPS2-Project. The process is described in [1]. **FIGURE 1** shows and overview of the System modelled. The test plant consists of a loop of 4 Solar collector Assemblys (SCAs), shown in the left part. The Energy Storage is a two-tank System with a hot molten salt tank and a cold molten salt tank (shown in the center part of the overview). on the right side of the overview, the steam generator is shown, which consists of 3 heat exchanger vessels. Additionally, a drainage system is integrated for emergency cases, but also integrated into the process as a distributor of salt from the cold tank.

As the novel technology in the project lies in the use of molten salt as the heat transfer fluid, top priority for training the operators lies in explaining the specialties when operating a parabolic trough CSP plant with molten salt. Therefore, transient modelling of the solar field, storage system and hydraulics network are the basis for the simulator with realistic behavior of all components in the salt cycle like pumps, valves, piping and tanks. The water/steam cycle is currently not included as a detailed simulation model.

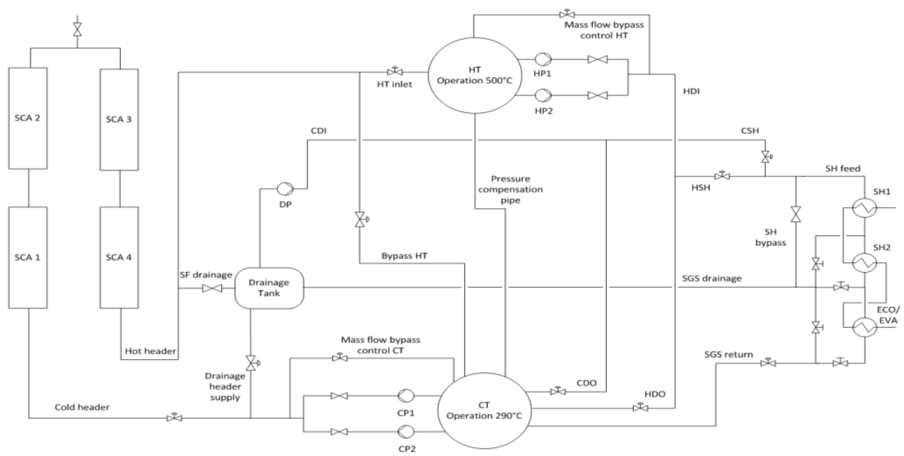


FIGURE 1. Overview of molten salt system.

Very important and also distinguishing from other simulation tools is the user-interface. The simulator is developed to give the operators a realistic look-and-feel of the future control system of the test plant, therefore the design is inspired by a common process control software. To enable the trainer to show the typical daily operation of the plant, daily series of weather data can be imported to the simulator. This features the basic relevant data for CSP plants: sun position, direct normal irradiation (DNI), wind speed and ambient temperature. To make future extensions and changes in the software easier, the program has a modular structure. Also, the software is designed to be portable and executable on nearly all standard windows-computers.

Used Tools

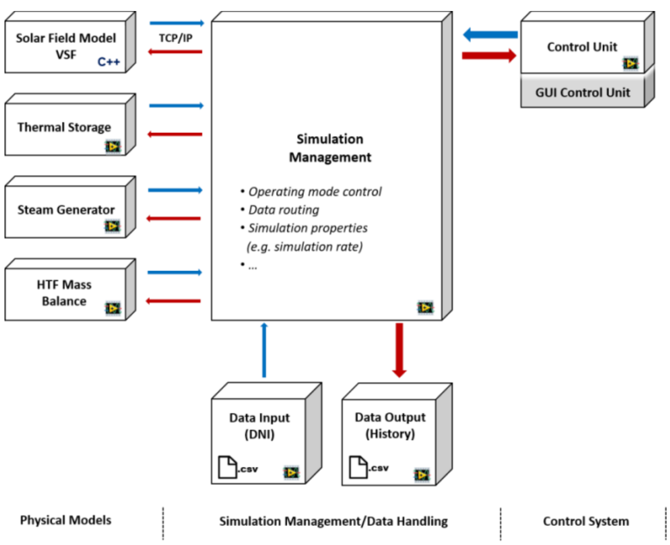
For transient simulation of the solar field, the simulator uses the Virtual Solar Field (VSF) model developed at DLR [5]. The Virtual Solar Field is a simulation tool that models the transient behaviour of a full-sized solar field including the header piping and fittings. VSF is based on coupling a hydraulic network solver to compute the flow distribution among the pipes in the field with a thermal solver to compute the temperatures with respect to the solar condition and the thermal losses in the pipes. Firstly, the hydraulic part is derived from methods used to solve water networks and computes the mass flow rate distribution within the parallel loops for the corresponding pump pressure and pressure drop in each pipe in the solar field. Moreover, throttling and control valves are modelled to hydraulically balance the field. The valves could also be used to alter the flow rates in the subfields or in the individual loops during field operation adding more flexibility to the field control and improving response to transient conditions. Secondly, the thermal part of the model is based on one-dimensional discretization of the continuity and energy equations for the flow in all receiver pipes (loops), and header and runner pipes. A simplified model for receiver pipes is adopted by using empirical relations to compute the thermal losses without modelling the glass envelop as in [6]. All fluid properties are computed as a function of the temperature using fitted data in literature, for example, in [12] for thermal oil, DOWTHERM A, and in [7] for solar salt. In addition, the model also offers a high degree of flexibility in setting the geometry of the pipes, the number of loops and subfields, the type and optical efficiency of collectors and receivers, and the insulation material in the header and runner pipes. All governing equations and implementation, as well as validation cases against real plant data provided by the commercial power plant Andasol-3 in southern Spain, are described in [4,8,9,10].

For the simulator management and the user-interface, LabView © was chosen as the programming language. It offers intuitive visual programming of process models and a wide variety of coupling options. Also very important for the development of the simulator, LabView supports flexible design of user interface graphics and their coupling with the control elements. Physical models of the hydraulics network and storage system is implemented as a Virtual Instrument (VI) in LabView. Furthermore, it contains the process control schematics derived from the functional description of the test plant.

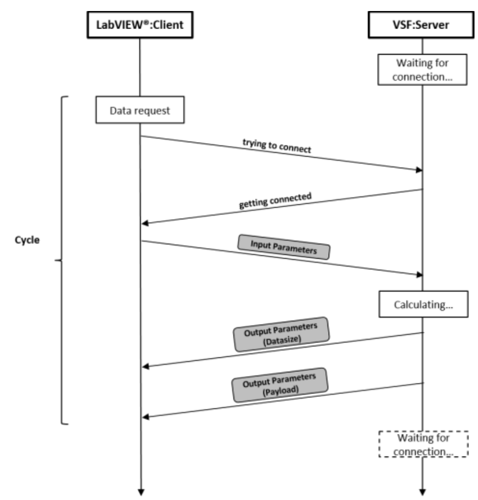
IMPLEMENTATION

Software Structure

The basic architecture is shown in **FIGURE 2** (a). The central element of the modular structure is the simulation management VI, which manages the data processing at each time step. It communicates the necessary input data for calculation of each time step to the other components, where the new status is calculated. As most of the models are implemented in LabView, data exchange happens inside the main program; variables are directly linked. As the Virtual Solar Field model is a separated Program based on C++, it communicates via a slim TCP/IP interface. The schematic for communication via TCP/IP is shown in **FIGURE 2** (b). The module HTF mass balance is the most complex part of the physical model. All pipes, valves, pumps and mass flow controllers are contained within this module. The thermal storage model calculates the status of the 2-tank storage system. The steam generator model is currently a place-holder and implemented as a simple heat sink for the salt system. The control unit VI features the graphical user interface (also called human-machine interface, HMI) and processing of all user-inputs during simulation like valve positions, controller set points. Data input is handled by sub-routines reading data from .csv files for weather data input in each time step.



(a)



(b)

FIGURE 2. Software Structure (from [3]).

The complete structure presented previously is inserted in the time management module of the simulator (**FIGURE 3**). Time management is realized as a while-loop, which execution speed is defined by the iteration time. The time step for the calculation is fixed at one second (simulation time). Together with the tme factor defined by the operator (from 1 time to 60 times real time) during initialization, the iteration time is defined for each execution of the calculation.

Example: with a time factor of 2 (double real-time) defined by the operator, the iteration time is 500 ms, as during one second real-time two times the simulation time of one second has to be computed. For each period of iteration time, the simulation management waits until all models have calculated and synchronizes the results.

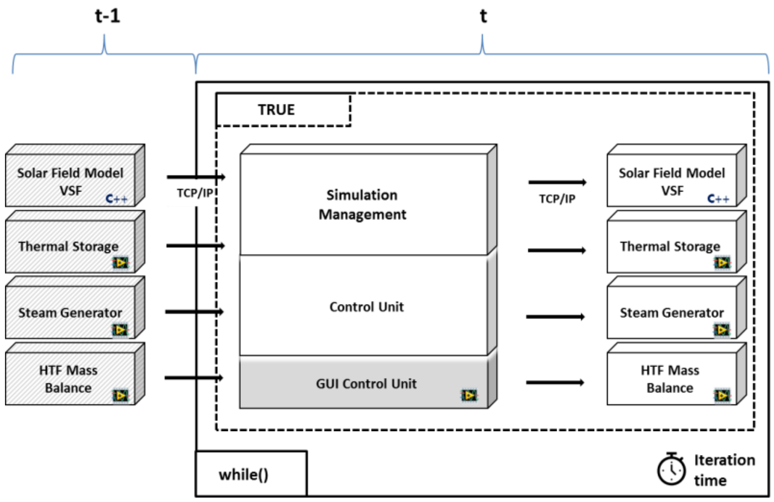


FIGURE 3. Time management (from [3])

HMI Design

The HMI design and functionality is built to resemble the later functionality of the test plant. Its design was done after the first draft of the plant control system for the HPS2 project. The main panel (**FIGURE 5**) contains an overview of the complete salt cycle plus the options to import or save data, starting and pausing the simulator and restart/end of the simulator. From the main view, the detailed view of all components can be opened. Plant control is done in the detailed view, where all controllers and set-points can be adjusted. The calculation values are updated live in all windows. The panel structure is shown in **FIGURE 4**. From each detailed view, the adjacent ones can be opened without going back to the main panel.

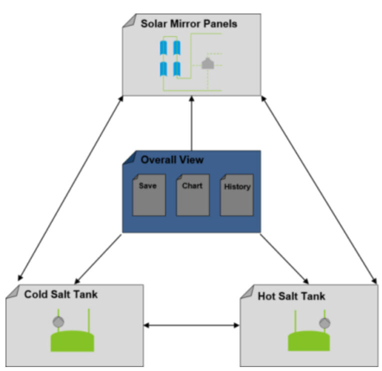


FIGURE 4. Panel structure [3].

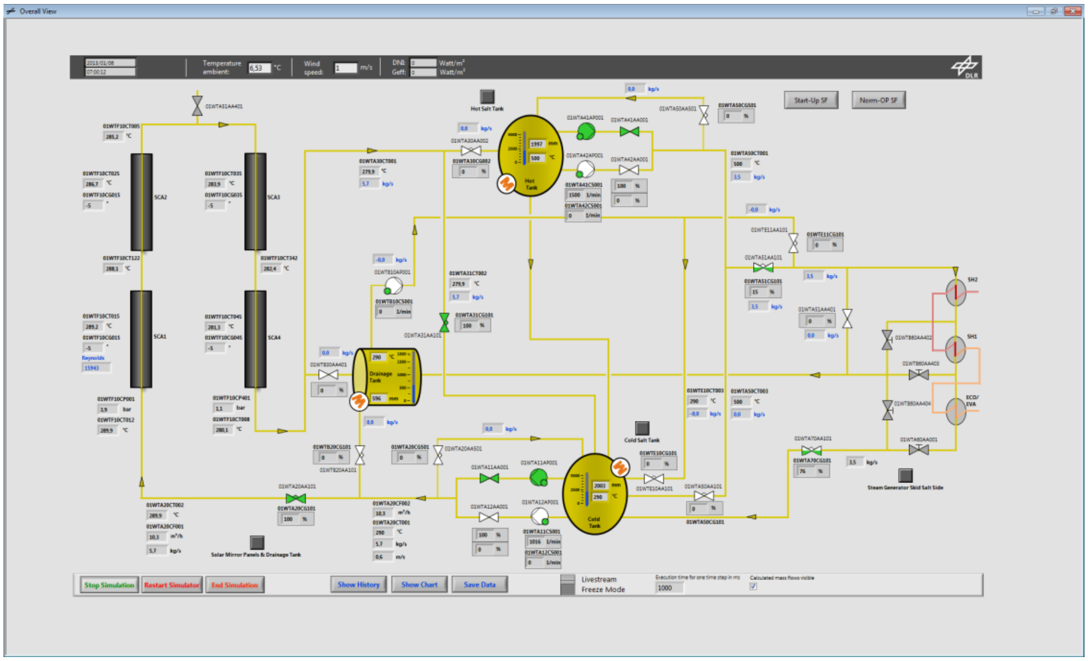


FIGURE 5. Main panel of the simulator.

All graphics are created according to the manual of the real process control software to give the operator a similar impression when using the simulator for training and later on controlling the test plant. **FIGURE 6**and **FIGURE 7** show a comparison between a screenshot of real process control software and the equivalent screen in the training simulator.

For live tracking of the process parameters and identifying trends, a live chart is implemented. This allows the operator to directly see the consequences of his actions and if further interventions are necessary.

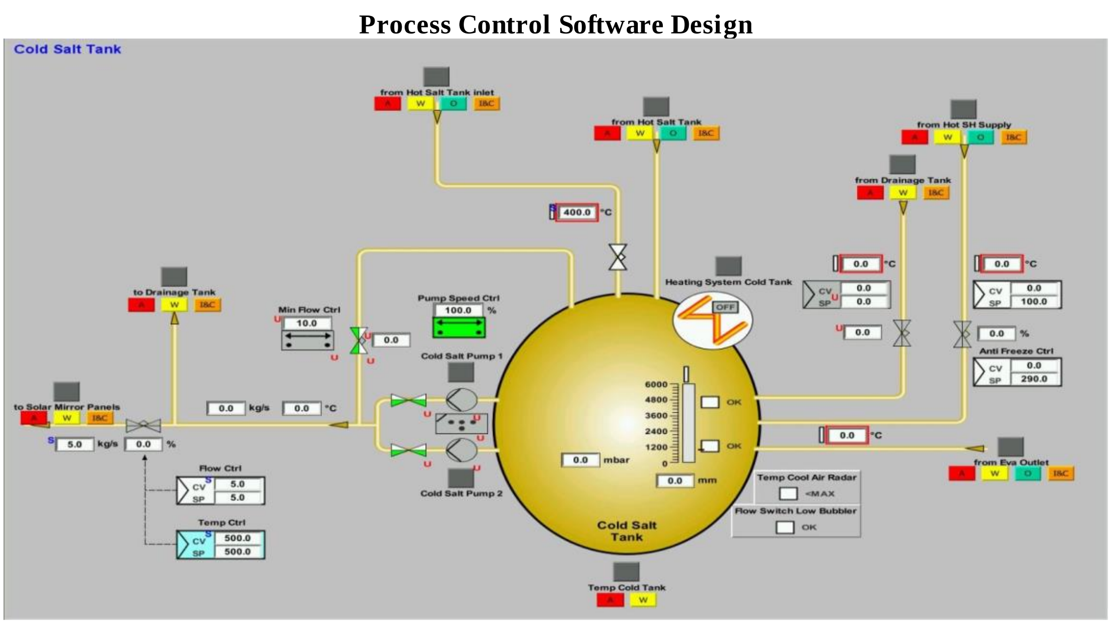


FIGURE 6. Comparison of HMI Design (1).

Simulator Design

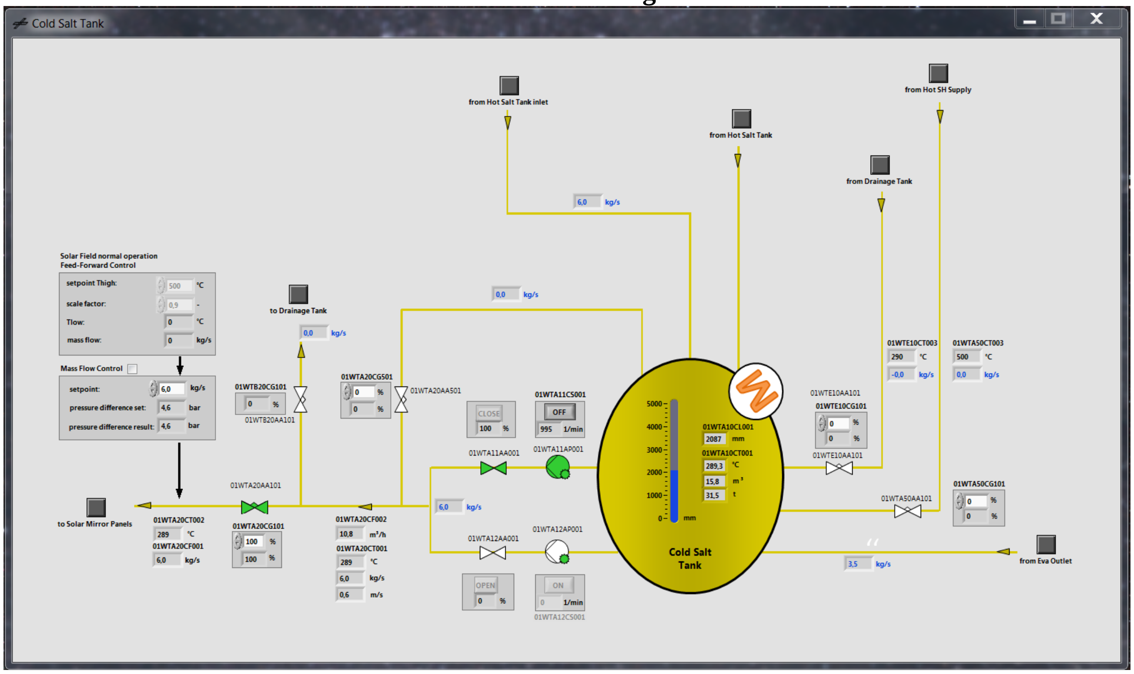


FIGURE 7. Comparison of HMI Design (2).

Simulation Models

Solar Field

A simplified version of the VSF is specifically tailored to model the single loop in EMSP with the specific salt mixture. This allows even faster computation times and easier integration with the training simulator interface. The interface is established by TCP/IP connections to transfer the data between VSF and the time management simulator that combines the different model components. In addition, the hydraulic network computation is expanded to account for the pump by-pass and the by-pass to the drainage tank. This allows the computation of the fluid distribution in the cold header section to be able to simulate different operation scenarios.

Storage and Hydraulics

The storage system is modelled with analytic equations for the mass and enthalpy content of each tank. The thermophysical properties of the ternary salt used in HPS2 are calculated in a separate VI, using empirical correlations for density, heat capacity and dynamic viscosity as a function of temperature. The equations used can be found in [11] for HeatecXL as a ternary salt mixture.

The hydraulics network is separated in two calculations, as the salt system is distributed into two independent sections via the thermal storage system. The solar field section is computed inside the VSF module. For the steam generator side, a hydraulic network plan was derived and the equations formulated with the same method as used in the VSF. The iterative solution for the flow distribution is then computed in LabView, using a solver based on the Newton-Raphson method. The driving pressure difference is calculated from the pump curves together with the pump RPM as a user input or controller value, depending on the operation mode. The hydraulic resistances are calculated from the pipe isometrics. All valves are implemented with their characteristic curves.

Controls and Alarms

The simulator features many controllers foreseen for the test operation of the research plant in Évora. The operator can use automatic modes for start-up of the solar field from night operation and normal daily operation of the solar field. For start-up, a chain of actions is defined to help the operator to raise the solar field outlet temperature to the desired one for normal operation. After reaching the target temperature, the mode changes to the normal operation mode, where salt mass flow is controlled to maintain a constant outlet temperature. The set-point is given by the operator through the interface shown in **FIGURE 8**. For better understanding of the plant behavior, the automatic modes can be enabled and disabled during simulation.

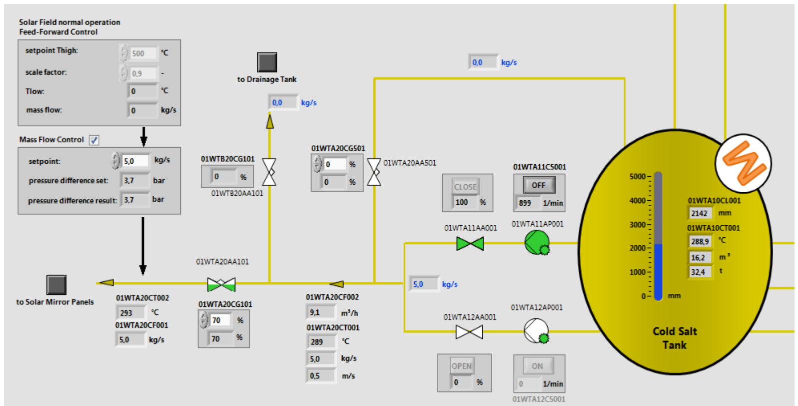


FIGURE 8. Control panel of cold salt pumps.

The simulator features alarm functions and reactions, which are implemented to protect the plant and personal in case of emergency. Like in the real test plant, the technical limitations of components are monitored constantly and safety actions are initiated when limits are exceeded. These parameters are set to the values as used for the test plant.

Steam Generator

The Steam generator is currently not modelled as a heat-exchanger. The model only consists of the hydraulic resistances of pipes and vessels, heat exchange is not modelled. To include the functionality for the salt cycle, it is a heat sink with user-defined outlet temperature.

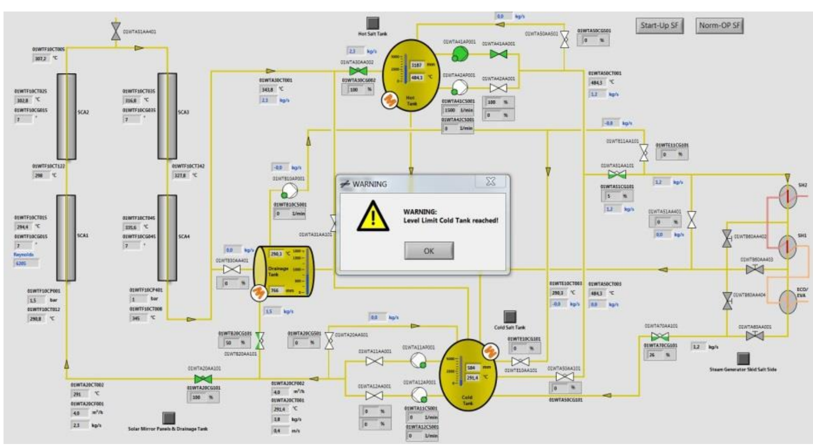


FIGURE 9. Level Alarm cold tank.

RESULTS AND DISCUSSION

Simulation Examples

A typical operation day can be reproduced and trained using the training simulator. The first step is to choose the weather profile of the day for simulation. For operator training, the trainer can choose the profile so the operator is not aware of the conditions to come during simulation. The initial status of the plant components is defined in the initialization window shown in **FIGURE 10**.

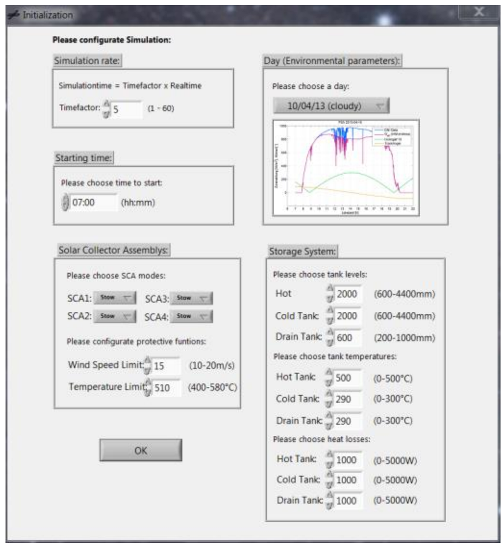


FIGURE 10. Initialization of simulator.

A usual day starts from night operation, with the hot tank nearly empty, the solar field and steam generator are cooled down. With sufficient DNI after sunrise, the operator can use the automatic start-up of the solar field or do it manually by setting the mass flow and focusing the collectors.

Temperatures, DNI and mass flow can be monitored in the chart. The automatic start-up sequence tries to maintain a constant temperature gradient. After reaching the desired outlet temperature of 500°C, the normal daily operation begins. The operator has to watch for temperatures and status of the thermal storage. Steam generation can be started, when enough salt is contained in the hot tank to ensure energy supply.

Operator's attention is drawn when conditions get unstable (**FIGURE 12**). In our example, some big clouds pass by the solar field. The DNI drops accordingly and starts to fluctuate when holes in the clouds move by. The automatic temperature control in this example was not able to cope with the situation, as the minimum allowed mass flow was reached, and a temperature drop occurs. The operator must decide whether to maintain operation and risk a process upset, as the lower outlet temperature will influence the steam generator or abort the normal operation and start recirculation of salt to the cold tank. When the clouds move away, DNI rises quickly. In this situation, the operator needs to watch closely to prevent over-temperature alarm in the solar field due to quick rising temperatures.

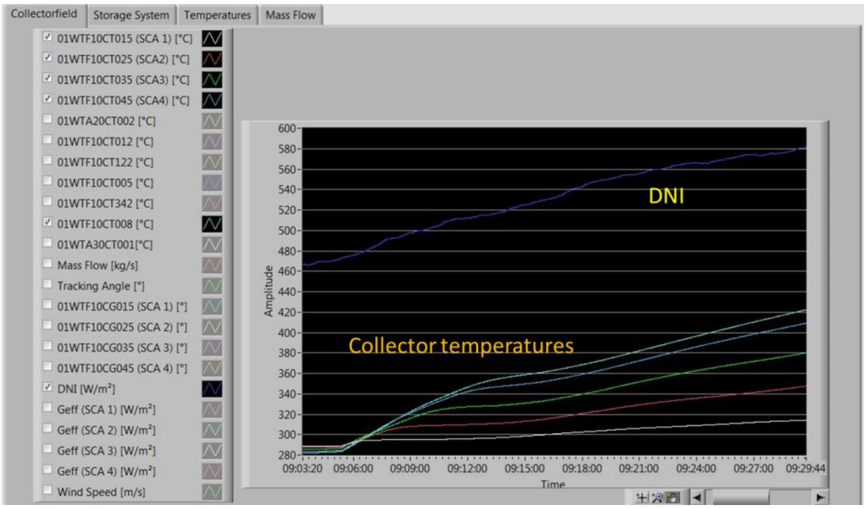


FIGURE 11. Live chart during start-up.

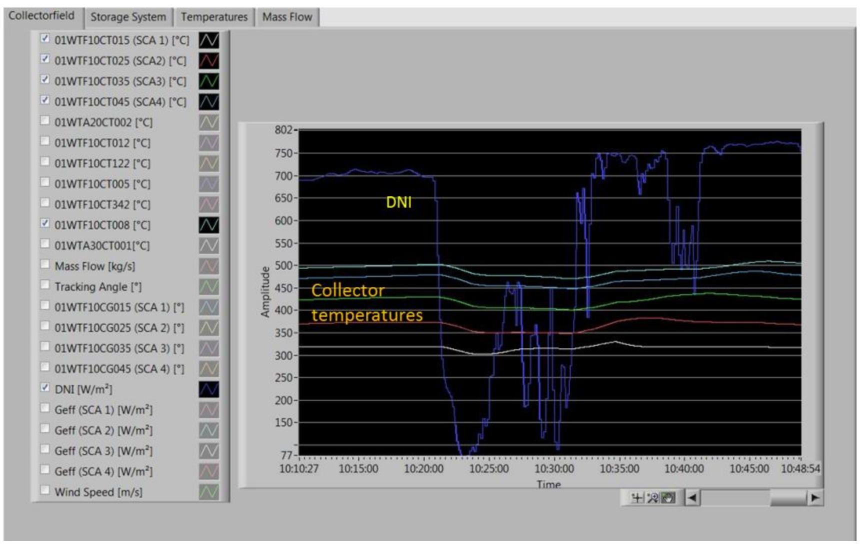


FIGURE 12. Live chart during DNI-drop.

In the afternoon or when solar irradiation drops too low, energy gathering becomes impossible as the desired solar field outlet temperature cannot be reached anymore. In this situation, the operator needs to cancel the solar field operation and shut-down the solar field. This is done manually; all actuators have to be set accordingly:

- Defocus the collectors;
- Set a proper mass flow according to the possibilities:
    a) Cool down the solar field slowly;
    b) Get the maximum heat content from the solar field and cool down quickly;
- Redirect the flow to the cold tank;
- Send collectors to stow-position;
- Set proper anti-freeze mass flow.

This closes the loop for the one-day operation of the test plant.

Conclusion And Lookout

The training simulator has proven the concept of coupling transient simulation models with a user-interface as a simple and efficient way to get a training tool for operators of solar-thermal power plants. In its current stage, it will be a valuable tool for the training course of the HPS2-operators. It will enable the trainer during the course to show all candidates of the operators team the basic behavior of the molten salt system. The basic structure of the control system can be learned by the operators using the simulator. Additionally, reactions in critical situations can be explained and also practiced beforehand of the commissioning without posing a risk to any equipment, humans or the environment.

Feedback from the operators can be given before commissioning of the test plan, which has the potential of increasing the operability of the test plant.

Another great value of the simulator lies in the possibility to test control concepts in advance of implementing them to the test plants control system. This will gain even more importance, when follow-up projects aim at advanced control strategies for molten salt parabolic trough operation.

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