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Operation and Training Tool for a Gas - Molten Salt Heat Recovery Demonstrator Facility

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Abstract

The supply of stable and reliable power is the main challenge that renewable power plants must tackle. Concentrating Solar Power (CSP), among renewable energies, is one of the most appropriate for large-scale energy production since it can efficiently store heat by means of Thermal Energy Storage (TES) systems. However, under unfavorable meteorological conditions, they may not be enough to satisfy the thermal demand of the power plant. With this aim emerges the HYSOL project, which presents an innovative hybridization configuration of CSP and biogas for a 100% renewable power plant. The demonstrator of this technology includes a gas - molten salt Heat Recovery System (HRS), a virtual gas turbine, a molten salt tank and an air cooler. The design of an operation and training tool for the HYSOL project, which includes a dynamic model of the demonstrator, is essential to evaluate the transient response, to test control schemes and to train plant operators. The design of such tool is described in this paper.

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Keywords: Dynamic modeling; heat recovery system; molten salt; solar thermal power

1. Introduction

Renewable energy power plants must address the issue of providing a stable, firm and reliable power output since this is their main drawback. Among all renewable energies, Concentrating Solar Power (CSP)is one of the most appropriate for large-scale energy production since it can efficiently store heat through Thermal Energy Storage (TES) systems, and thus it can dispatch energy on demand.

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However and because of economic reasons, TES sizes may not be able to meet the power plant demand, especially under unfavorable meteorological conditions. Nowadays, this issue is tackled by hybridization with fossil fuels, where two technologies are commonly used: CSP plants with auxiliary fossil fuel heaters, mainly used as back-up systems but not intended for electricity production[1] and integrated solar combined cycle power plants, where the solar energy contribution is still small[2].

Nevertheless, CSP keeps being an active research area, issues such as environmental pollution, concerns about sustainability and rising cost of fossil fuels encourage research and investment into alternative solutions. One of them is multiple energy source hybridization, such as solar power and biomass or biogas. Biogas has the advantage than can be more efficiently delivered liquefied in pressurized tanks or through distribution networks. With the aim of ensuring appropriate supply as well as environmental impact assessment studies of biogas use emerges the HYSOL project[3 4].

The HYSOL consortium is composed of research institutions, as well as industrial partners, where the project coordinator is ACS/Cobra. The main goal of the HYSOL project is the study, design, optimization and construction of a pre-industrial demonstrator based on an innovative hybridization configuration of CSP and biogas for a 100% renewable power plant.

CIEMAT-PSA is the coordinator of the *dynamic modeling and advanced automatic control* work package. The dynamic model of the pre-industrial demonstrator will be used to evaluate transient responses (i.e, start-ups, shutdowns, etc.), for the design, testing and validation of advanced control strategies and is the keystone in the training tool for plant operators.

This paper presents the design and development of an operation and training tool for the HYSOL demonstrator; it is structured as follows: Sec. 2 describes the HYSOL technology and demonstrator, Sec. 3 presents the design of the demonstrator model, Sec. 4 introduces operation considerations and control techniques, Sec. 5 gives details about the Supervisory Control And Data Acquisition (SCADA) system, Sec. 6 shows the operation and training tool, finally Sec. 7 summarizes the main conclusions and ongoing work.

2. HYSOL Project

The HYSOL project - *Innovative Configuration of a Fully Renewable Hybrid CSP Plant* from the EU 7^{th} Framework Programme is in the *Theme Energy 2012.2.5.2 - hybridization of CSP with other energy sources*. The HYSOL consortium is composed of partners from four European countries, defining a multidisciplinary team, with partners devoted to research activities: CIEMAT-PSA, ENEA, UPM, DTU/MAN/SYS and SDLO-PRI, together with industrial partners: ACS/Cobra, AITESA and IDIE. The project coordinator and promoter is ACS/Cobra, a company with a vast experience in the development, building, operation and maintenance of industrial facilities and power plants.

2.1. HYSOL Technology

The HYSOL project focuses in the development of an innovative configuration based on a CSP plant with a molten salt thermal TES system, steam turbine (a Rankine cycle, if an ideal cycle is considered), gas turbine (an open Brayton cycle) and a flue gas - molten salt Heat Recovery System (HRS). One of the proposed HYSOL schemes is shown in Fig. 1. Nevertheless, there are several HYSOL configurations, since the HYSOL concept can be applied to Parabolic-Trough Collectors (PTCs) or tower based CSP plants with direct or indirect TES systems. The HYSOL concept depicted in Fig. 1 corresponds to a tower CSP plant with direct TES, where the working fluid, as well as the storage fluid, is molten salts. There are mainly three operating modes; they are briefly summarized as follows.

1. Molten salt thermal energy from the solar field is stored in the hot molten salt tank; this energy is used to produce electricity by means of a steam generator in a Rankine cycle, whereas the energy excess is kept in the hot tank. The steam generator outlet molten salts are stored in the cold tank.
2. When the solar field cannot provide enough energy to maintain the steam turbine nominal operating conditions and the TES system has enough thermal energy, molten salt keeps flowing from the hot tank to the steam generator as described in point 1.
3. When the solar field, as well as the TES system, cannot provide enough thermal energy to the Rankine cycle, the gas turbine in the open Brayton cycle will produce electricity. Furthermore, the flue turbine gases will be used to

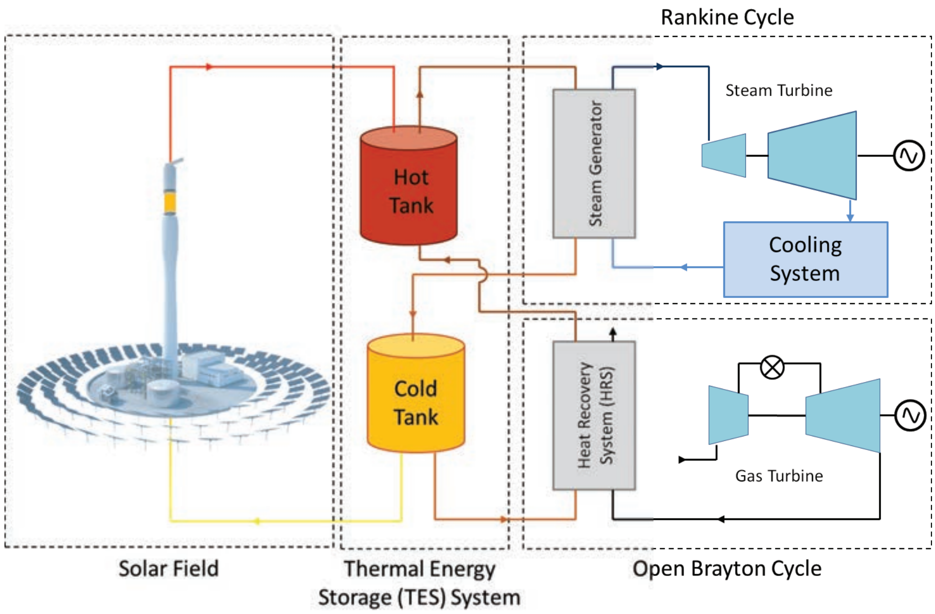


Fig. 1: HYSOL configuration with tower solar thermal power plant and direct TES

heat molten salt from the cold tank in the HRS. The hot molten salt coming from the HRS will be stored in the hot tank, which will be used again in the Rankine cycle as described in point 2. Additionally, the flue gases from the HRS can be used to optimize the plant performance.

2.2. *HYSOL Demonstrator*

The Manchasol solar thermal power plant, owned by ACS/Cobra, is currently being adapted as a demonstrator of the HYSOL technology. The demonstrator focuses in the gas-molten salt HRS, an sketch of it is shown in Fig. 2. Its main components are briefly introduced in the following lines.

- *Virtual gas turbine.* This component, with the appropriate control system, emulates a gas turbine with afterburner like the one considered in the HYSOL configuration. This element is composed by an air intake system, a fan, a gas tank, and a combustor, cf. Fig. 2.
- *Heat Recovery System (HRS).* The HRS allows to recover thermal energy from the virtual gas turbine flue gases, thus heating molten salts in the same ways as in the HYSOL configuration.
- *Molten salt tank.* Once molten salts are heated in the HRS, they are stored in this tank, therefore this tank emulates the hot molten salt tank.
- *Air cooler.* An air cooler emulates the molten salt discharging process, i.e. the energy transfer from the hot tank molten salt in the steam generator. Since a cold tank has not been included in the demonstrator, the air cooler shall have to operate following the load of the HRS.

CIEMAT-PSA, as coordinator of the *dynamic modeling and advanced automatic control* work package, is in charge of the development of a dynamic model (cf. Sec. 3), a control scheme (cf. Sec. 4), the SCADA system (cf. Sec. 5), as well as an operation and training tool (cf. Sec. 6). In order to calibrate and validate some of the developed dynamic models, before its final tuning in the Manchasol plant, the CIEMAT-PSA molten salt testing facility [5] was used as a mock-up test bench [6,7,8].

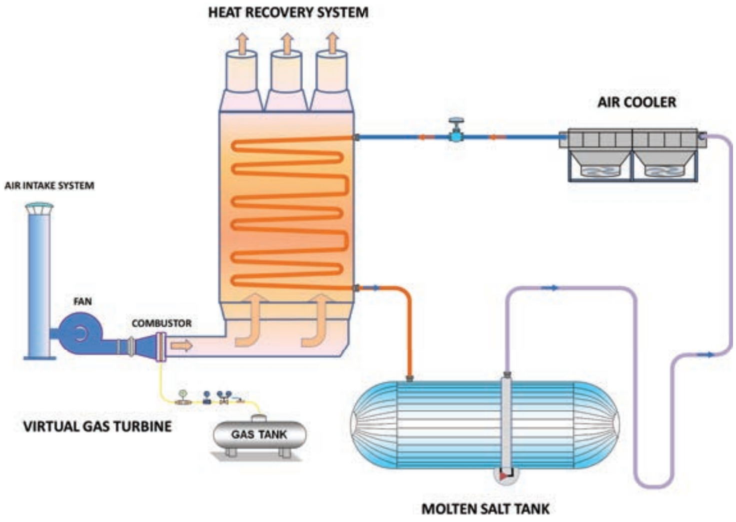


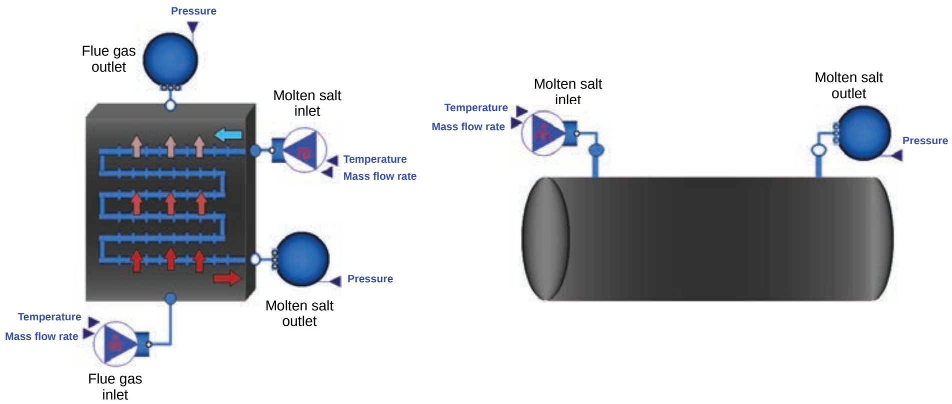
Fig. 2: HYSOL demonstrator configuration

3. Demonstrator Dynamic Model

The demonstrator dynamic model is composed by each one of the main components previously described in Sec. 2.2. Each component has been modeled independently. Secs. 3.1-3.4 describe each one of these models, whereas Sec. 3.5 presents how the whole model was developed.

3.1. Virtual Gas Turbine Model

The virtual gas turbine dynamic mathematical model will be obtained from measured input-output data. Since, up to now, the HYSOL demonstrator facility commissioning has not been carried on, the first version of this component is a first order model based on manufacturer data. The inputs are the ambient temperature, the heater modulation and the air mass flow rate setpoint. The model outputs are the air outlet temperature and mass flow rate.



(a) Heat recovery system model icon and inputs (b) Molten salt tank model icon and inputs

Fig. 3: Dynamic Modelica models

3.2. Heat Recovery System (HRS) Model

The HRS model has been developed using the Modelica language[9] and the Dymola tool[10]. It is based on first principles. One-dimensional dynamic mass, energy and momentum balances in the flow direction are considered for gas and molten salts. One-dimensional energy dynamic balances in the HRS structure is also considered. Convective heat transfer mechanisms rely on appropriate heat transfer correlations, whereas radiation heat transfer processes are based on average emissivities values. Pressure drops in both fluids are calculated according to correlations available in the literature.

The HRS model icon and inputs are shown in Fig. 3a. The model inputs are: the inlet molten salt and flue gas temperatures and mass flow rates, and in order to close the hydraulic circuits the outlet molten salt and flue gas pressures. This model calculates the outlet molten salt and flue gas temperatures.

The dynamic HRS model was validated at steady-state conditions against results obtained from other partners models, i.e. against results obtained from IDIE steady-state model, developed in ThermoFlex[11], and AITESA engineering calculations for the design of the demonstrator HRS.

3.3. Molten Salt Tank Model

The molten salt tank was also modeled using Modelica and considering first principles. The model has two molten salt channels, an inlet and an outlet, cf. Fig. 3b. Mass and energy molten salt balances are considered in this model. The model also calculates the molten salt level in the tank. The molten salt extraction from the tank model is performed by means of an ideal pump.

The horizontal cylindrical molten salt model was validated, in terms of molten salt temperature and level, against real data obtained from experimental campaigns in the cold tank, which is also a horizontal cylindrical tank, of the CIEMAT-PSA molten salt testing facility.

3.4. Air Cooler Model

The air cooler at the demonstrator facility includes its own Programmable Logic Controller (PLC) to maintain the desired molten salt temperature at the inlet of the HRS. In the first version of the simulator, the air cooler has been modeled as an ideal one, therefore it is assumed that it can dissipate the required amount of the molten salt thermal energy to match the outlet temperature imposed to the model. Once the experimental campaign starts, a mathematical model based on input-output data will be included to simulate the air cooler dynamic response under different inlet temperature disturbances and temperature setpoint changes.

3.5. Models Integration

Since some models are developed using LabVIEW[12] (virtual gas turbine and air cooler models) and the others using Modelica (HRS and tank models), the Functional Mock-up Interface (FMI)[13] has been used to integrate them and develop the demonstrator dynamic model.

FMI defines an open interface to be implemented by an executable called Functional Mock-up Unit (FMU). The FMI functions are used (called) by a simulator to create one or more instances of the FMU, called models, and to run these models, typically together with other models[14]. FMI is a tool independent standard for the exchange of dynamic models and for co-simulation. The primary goal is to support the exchange of simulation models even if a large variety of different tools are used. The FMI was developed in a close collaboration between simulation tool vendors and research institutes.

FMI is used in the demonstrator dynamic model to import the Modelica models in LabVIEW by means of a FMU of such Modelica models, which is generated by the Dymola tool, cf. Fig. 5.

4. Control and Operation

The simulator tool must represent as close as possible the HYSOL demonstrator located at Manchasol solar plant. Therefore, different operating modes and control strategies are included. Three operating modes will be considered initially:

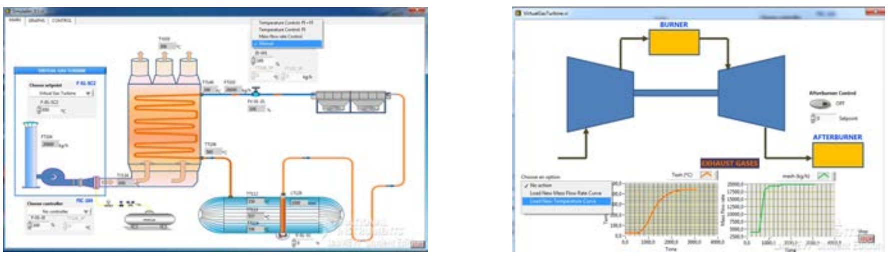
- Startup: different turbine startup curves can be defined to be simulated with the virtual gas turbine. In this stage, the HRS can start in a cold or warm mode so it is crucial to follow the manufacturer, AITESA, operating recommendations in order to operate the system in safe conditions.
- Running: once the startup stage has finished, the system is ready to evaluate different operating conditions in the main variables. This mode can be also used to test several control loop responses under different disturbances and setpoint changes.
- Shutdown: as in the case of the startup stage, different turbine shutdown curves can be simulated. A turbine simulator with an afterburner is also configured to evaluate the behavior of the exhaust gases control loop to maintain HRS safety conditions such as maximum thermal gradients.

The control loops have been design and analyzes in Matlab/Simulink [15], however they are implemented in LabVIEW in the operating and training tool. Four control loops are included in the simulator:

- HRS outlet molten salt temperature with molten salt mass flow rate as control variable. Two PID controllers in cascade mode are used; the slave PID acts over a valve opening to control the molten salt mass flow rate, and the master PID controls the molten salt temperature using the mass flow rate setpoint as control variable. This master controller is combined with a feedforward action in parallel configuration.
- HRS outlet molten salt temperature with gas mass flow rate as control variable. A PID controller is combined with a feedforward action in parallel configuration to calculate the gas mass flow rate setpoint that must be sent to the heater generator. This control loop is included only for model validation in the demonstrator since the gas mass flow rate is prescribed by the gas turbine in the HYSOL configuration.
- Molten salt pump. This control loop regulates the pump variable speed in order to maintain the pump operating close to the maximum efficiency conditions. This controller is of the gain-scheduling scheme kind and takes into account the molten salt valve opening in order to consider different hydraulic load losses.
- Afterburner control loop. This virtual PID controller maintains the desired gas inlet temperature in the HRS despite gas turbine exhaust gases disturbances.

5. SCADA System

The training system interface has been developed LabVIEW. The communication with the HYSOL demonstrator model and control loops is carried out with the LabVIEW MathScript node. Snapshot of the main and virtual gas turbine windows are presented in Fig. 4.



(a) Main window (b) Virtual gas turbine window

Fig. 4: SCADA snapshots

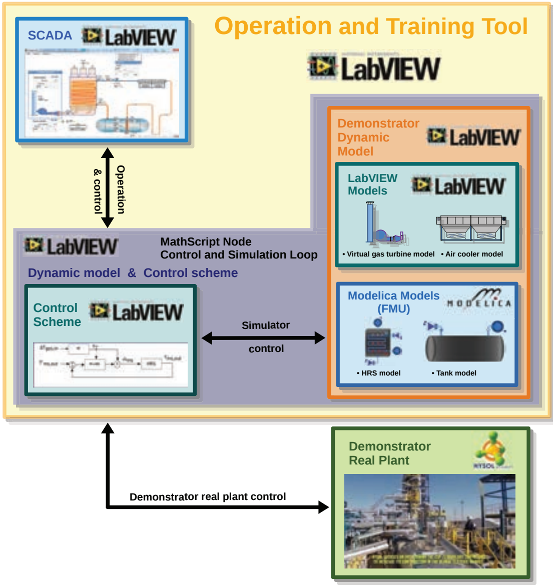


Fig. 5: Operation and training tool software architecture

6. Operation and Training Tool

The software architecture of the operation and training tool is sketched in Fig. 5 and it is composed by three main elements.

- *SCADA system.* The operating mode can be established in the SCADA system: simulation, real plant and hybrid modes, operating modes are explained below. The SCADA system also allows to set the control scheme setpoints and shows the demonstrator simulation results, real data or both. It has been introduced in Sec. 5
- *Control scheme.* The control scheme controls the demonstrator model or real plant inputs according to the setpoints established in the SCADA system; it receives feedback from the dynamic model or the real plant depending on the operating mode. The control scheme was presented in Sec. 4.
- *Demonstrator dynamic model.* This dynamic model simulates the behavior of the demonstrator real plant. The different models which compose it and how they have been developed and integrated is explained in Sec. 3.

The Modelica models, the HRS and thank models,, are exported from Dymola as a FMU. This FMU is then imported in LabVIEW, this allows the communication between these models and the remaining models, control scheme and SCADA system, cf. Fig. 5. For simulation and control purposes, the LabVIEW control and simulation loop together with the MathScript node are used. The operation and training tool is flexible and can work in different modes.

- *Simulation mode.* In this mode, the SCADA system communicates with the control scheme which controls the demonstrator dynamic model. This mode is useful for studying the system dynamics, for testing control strategies and to train plant operators.
- *Real Plant mode.*The SCADA system also communicates with the control scheme in this mode but it controls the demonstrator real plant instead of the dynamic model. This mode is intended for testing and validating new control strategies, which were previously tested in simulation.
- *Hybrid mode.* In the hybrid mode, the control scheme simultaneously controls the demonstrator real plant as well as the model, where feedback is provided to the control scheme from the real plant. This mode is useful

for estimating and comparing deviations between the model and the real plant. It is also useful for calibrating and validating dynamic models and control strategies.

7. Conclusions and Ongoing Work

This paper has presented the HYSOL project, its technology and demonstrator. The dynamic HYSOL demonstrator model and its components have been also described. After that, operation and control schemes have been presented. The development of an operation and training tool, including a SCADA system, has been detailed, where its advantages and working modes have been highlighted. The operation and training tool presents itself as a useful tool for studying the system dynamics, for testing and validating control schemes in simulation, as well as against the real plant, and to train plant operators.

Ongoing work includes performing an experimental campaign in the HYSOL demonstrator in order to calibrate and validate the dynamic models and the control strategies, considering a wide range of operating conditions and disturbances which will ensure an optimal control of the plant.

Acknowledgements

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