Object Oriented Modelling and Simulation of Parabolic Trough Collectors with MODELICA

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Abstract

The design of advanced control systems to optimize the overall performance of Parabolic Trough Collectors solar plants with Direct Steam Generation is currently a priority line research at CIEMAT-PSA. The development of dynamic models for use in simulation and control of this type of solar power plant is presented in this article, focused on the DISS solar plant. The developed model is based in the thermohydraulic modelling framework ThermoFluid, within the MODELICA modelling language. The DISS facility is presented and main modelled components are presented as well as the respective modelling assumptions. A simulation of a real experiment realized and the predicted model values are compared with the real measurements.

1 Introduction

This paper presents the current status of the research performed within the framework of modelling and simulation of Parabolic Trough Collectors (PTC) in the scope of Solar Power Plants. The work is mainly oriented to the development of dynamic models of solar energy plants to be used in the design of automatic control systems aimed at optimizing overall performance.

Figure 1: DISS facility at Plataforma Solar de Almería, in Almería (Spain).

The system used as test-bed plant is the DISS facility, see figure 1. Actually, it is a row arrangement formed by eleven PTCs with a combined length of 500 m, working as a 1 MW_t solar power plant belonging to CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas - *Research Centre for Energy, Environment and Technology*), Research Centre owned by the Spanish Ministry of Science and Education. This solar plant is located at the Plataforma Solar de Almería (PSA), Southeastern Spain. A joint project between CIEMAT-PSA, the University of Almería (UAL), the National University of Distance Education (UNED) and the University of Seville (US) is being carried out in order to develop models and control systems to automatically control these type of plant. The model presented in this paper will be used in the design of hybrid model predictive control and intelligent control schemes to optimize plant performance, even under start-up and shutdown situations and in spite of highly variable load disturbances due to the daily cycle of solar radiation and passing clouds.

2 The Parabolic Trough Collectors Facility DISS

In this section, an overview of the basic components and operating procedures for the DISS plant is presented. A schematic diagram is shown in figure 2, in which the most important components are depicted.

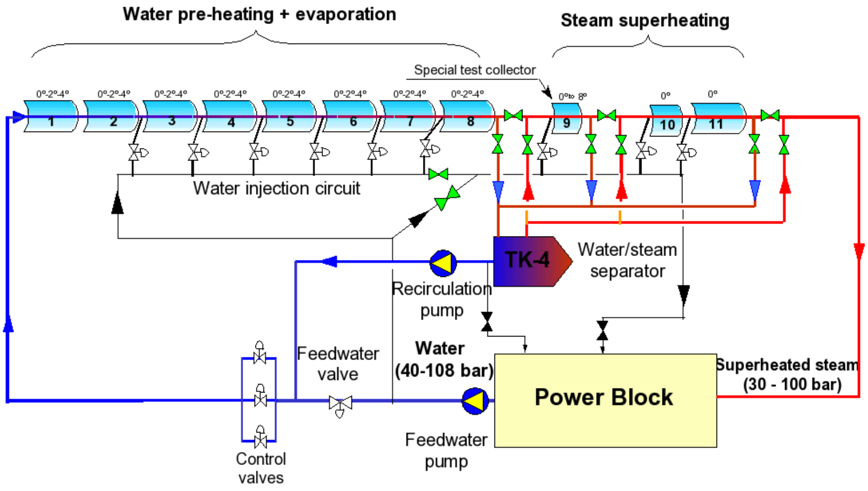

Figure 2: Schematic diagram of DISS facility at PSA

There are three main different operational configurations of DISS facility. In all of them, the operation is based on the concentration of incoming direct solar radiation onto the absorber tube located in the geometrical focal line of a cylindric-parabolic mirror. As the sun position changes during the day, each PTC of the facility has to change its orientation as the solar radiation vector does. The absorber tube in each PTC acts as an energy exchanger, receiving solar energy and transferring it to a thermo-hydraulic circuit with a heat transfer fluid (HTF) as the medium. Traditionally in PTCs the HTF used has been thermal oil, which presents major drawbacks with respect to the water-steam medium used in the DISS facility, as explained in [16]. In addition of the PTCs, the facility is composed by the following components:

- Water-steam separator. Only used in *recirculation* operational mode.
- Pumps: feedwater and recirculation. The former pumps subcooled water into the row and the latter drains saturated liquid water from water-steam generator.
- Injectors. Are actuators to control temperature by injection of subcooled water from the injection line.
- Valves. They let the system be configured in any of the three main operational modes and for control purposes.

- Power Block. It is a component representing any possible load process consuming the regulated outlet of thermal power from the plant. In this case, for water conservation during the experiments, the current implementation returns the thermodynamical state of the outlet superheated steam to subcooled liquid to be pumped by feedwater pump.

Figure 3 shows the three main operational modes, with their pros and cons:

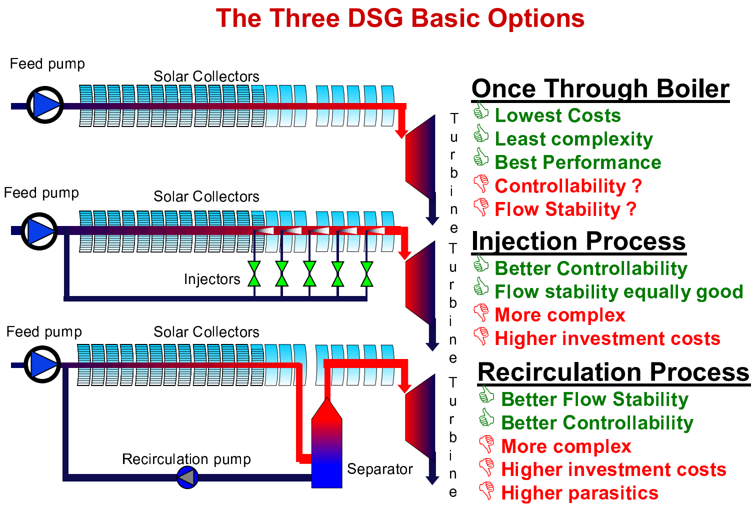

Figure 3: DISS plant operational modes

- *Once-Through*. Lowest investment costs and engineering complexity, although great controllability problems and instabilities during operation. The systems works as a distributed once-through boiler fed with subcooled water and superheated steam at outlet, at nominal operating conditions.
- *Injection*. Highest investment costs, although better controllability and less instabilities. The system works as a once-through evaporator in which, at certain points in space, an injectors arrangement help to control spatial temperature distribution along the whole row.
- *Recirculation*. Second highest investment costs, with a good controllability. In this mode, the water-steam separator placed in the row decouples two effective once-through evaporators: the first one is a flooded evaporator and the second is a dry-expansion one.

In all cases, the flow temperature at the outlet superheated steam must be controlled. Control of the facility has been one of the main efforts that CIEMAT has developed, see ([12]), although the lack of robust dynamic models for control is a major obstacle in the control system development.

CIEMAT is currently interested in these two configurations:

1. *Recirculation*. It offers the trade-off between investment costs and plant controllability. This configuration will be preferred for experimental applications.
2. *Once-through*. Spurred by the lowest investment costs, theoretical work must solve controllability and instabilities through the development of integral control systems for this configuration.

The modelling work presented in this paper will focus on *once-through* configuration for two reasons. First, the process is not observable by means of the actual sensors in the facility; it is not possible to measure/estimate specific enthalpy or mass fractions in transient experiments in the two-phase sections, which in some operational points achieve 50% of the whole length. Second, it is supposed the greatest disagreement between the model and experimental data should appear in this configuration. So any other configuration modelled with components validated in *once-though*, should show a closer agreement with experimental measurements.

In *once-though* operation mode the DISS acts as a *once-through* evaporator of 500 m length with subcooled water at the inlet and superheated steam at the outlet, in nominal operating conditions. A cascade local control loop for the feedwater pump and an outlet controlled valve define boundary conditions for the system. The final objective of the model is to predict the transient behavior of the thermodynamic variables associated with the thermo-hydraulic output power of the evaporator (temperature, pressure, specific enthalpy, etc.), when the external disturbances (mainly concentrated solar radiation, ambient temperature, inlet subcooled water temperature and inlet subcooled injector water temperature) and controllable inputs (inlet subcooled mass flow rate, inlet final injector mass flow rate and outlet superheated steam pressure) change.

3 Object Oriented Modelling of DISS

In this paper we will concentrate in the modelling of the thermo-hydraulic part of the system, skipping the rest the remaining subsystems (pneumatic, mechatronic, etc.) needed to maintain the proper instantaneous orientation of the PTC group, and assuming a known input radiation power in the absorber pipe, as a consequence of the radiation reflected in the cylindric-parabolic mirrors. For a detailed explanation of this subsystems read [16] and [15].

Due to the fact that the main phenomena of interest is the thermofluid dynamics, the object oriented Modelica language ([8]) has been used to develop these models with the Dymola tool ([4]). Within this modelling language the ThermoFluid library ([11],[5]) is a framework over which develop own libraries and final component models ready to be instantiated as components for simulations. The authors believe this library is an important reference in the framework of object oriented modelling of thermofluid systems with Modelica and its existence makes it unnecessary, in most cases, to develop thermo-hydraulic models from scratch. Instead, the models can be designed by inheritance and aggregation from base classes in the ThermoFluid framework.

The work analyzes each of the components of the thermo-hydraulic water-steam circuit and explains the modelling assumptions, trying to justify each one as they are oriented to get - by means of the symbolic manipulations that Dymola tool performs - a not high index DAE system for the complete model, in which the number of nonlinear algebraic loops is minimized. For this purpose, all the components are classified, following the modelling methodology derived from the Finite Volume Method (FVM) [9], in Control Volumes (CV in ThermoFluid nomenclature) and Flow Models (FM in ThermoFluid nomenclature).

In some cases information about the future control system architecture to be implemented is introduced in the modelling phase. This methodology, from a strict point view, breaks the sequencing work of first model and then design the control system based in this model. But it helps to simplify the design of the models and enhances the numerical behavior of the whole modelled system in the simulation execution phase, without a significant loss of accuracy.

Due to the existence of components whose internal implementation may vary depending on the modelling hypotheses, the polymorphism and the Modelica language constructs for classes and components parameterization has been extensively used and specifically applied in PTCs models.

Figure 4 shows the developed Modelica model of the DISS facility working in *once-through*.

3.1 ThermoFluid usage

The dynamic behavior expected to be predicted by the models is mainly the thermal one, so the steady state formulation for the momentum balance is selected for the utilized ThermoFluid base classes. The selected time scales for the thermal dynamics are for control design and simulation purposes.

The thermo-hydraulic interface for all the models is formed by connectors from the *Interface* package, for single component media and steady-state momentum balance statement.

The modelling methodology adopted from the beginning for the design of the classes was: *if there exists any class in ThermoFluid that implements the physical phenomenon to model, use it with the corresponding parameterization. If not, design the classes using inheritance from the high level partial classes from ThermoFluid; in other cases then use proper ThermoFluid interfaces and base classes and develop the class with the lacking behavior expressed in differential and algebraic equations from first principles.*

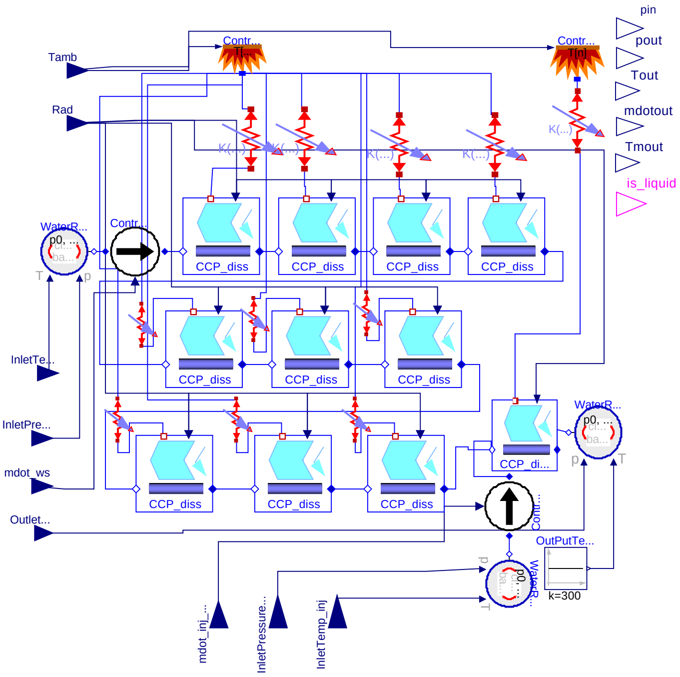

Figure 4: Modelica model of DISS plant in *once-trough* configuration.

3.2 Designed Classes

In the next subsections the most important components models will be detailed and the modelling hypotheses will be explained and justified.

3.2.1 Pumps and Injectors

In this kind of active FM [11], the authors decided to make a simplifying assumption based on the gained experience in control of Parabolic Trough Fields with thermal oil as medium, case of Acurex field of CIEMAT-PSA [2], [3], and water-steam as medium in DISS facility [16], [12]. This assumption consists that the water pumps are controlled in a cascade scheme [1] with a local control loop whose dynamics is much faster than the rest of the thermohydraulic system. This assumption has been experimentally validated in blowers and water pumps, and helps simplify these components models until the possibility of modelling them as steady-state quasi-ideal mass flow rate generators. This approximation avoids the time-consuming work of fitting the nonlinear multivariate curves of the pumps and injectors. So, the algebraic equation for these components is $\dot{m} = \dot{m}_{ref}$, where $\dot{m}_{ref}$ is the setpoint of the local pump/injector control loop and it is assigned in a connector to the model, as can be seen in figure 4.

3.2.2 Parabolic Trough Colectors

The PTC is the most important component in the facility. Its aim is to carry most of the part of the solar direct incident irradiance in the mirror to the absorber tube. To achieve this aim, the manufacturing process uses advanced material sciences and technologies to minimize the power loss in direction to absorber tube. In [6] and [16], an analysis of the energy flows into the absorber from the sun is developed.

In the figure 5, the main components of a PTC are shown, and enumerated in the following:

- Cylindric-Parabolic mirror surface. It reflects the incoming direct solar radiation to the focal line of the mirror.
- Absorber metal pipe. It absorbs the major part of the energy reflected by the mirror.
- Energy loss to the environment by conduction-convection and radiation.

- Medium model, that is, the HTF. In the case of this work, water-steam is the selected medium.
- Distributed CV, with a discretization level of n in which mass, energy and momentum is conserved.

For modelling effects, this component could be considered as a heat exchanger composed of one pipe with water and/or steam as media fluid, and a circular wall allowing thermal interaction with the fluid. This hex is fed by solar energy through the external perimeter of the circular wall and, at the same time, some energy flow is leaving through this external perimeter by conduction-convection and radiation processes.

The length of the water/steam pipe is 50 m. and under normal operating conditions the inlet/outlet flow could be in any of the three states: liquid water, two-phase mix of saturated liquid and vapor, or superheated steam. This depends on the position of the PTC in the row, in addition to the incident solar radiation in the row.

Thus the dynamic behavior of each PTC will vary along the DISS row depending on the thermodynamic and transport state of the water/steam in each PTC. With the configuration shown in figure 5, the PTC is fully discretized in n CVs in the major length direction, in which mass, energy, and momentum balances are stated. Momentum conservation is stated in staggered CVs with respect to those ones in which mass and energy balance is stated; see [9], [13] and [11]. The number of CVs, n, is a trade off between accuracy and computing cost, so the final choice is the minimum n that models dominant dynamics for control purposes. Currently we are working with values in the interval $[2,5]$ per PTC. The wall is discretized with the same discretization level.

To solve the PDE system stated from balance equations, ThermoFluid provides partial classes [11] in which the discretization with the Finite Volume Method (FVM) ([9]) is applied. One of these classes is *ThermoFluid.PartialComponents...Volume2PortDS_pT*, which implements this mass, energy and static momentum conservation equations in a staggered grid formed by n subvolumes. For the solid media, there exists final use classes that implement energy conservation in distributed solids, *ThermoFluid.Components.HeatFlow.Walls*.

To close the system of equations, it is mandatory to introduce the heat transfer coefficient between the water-steam flow and the solid media. This coefficient depends of heat transfer correlations using adimensional fluid numbers (Reynold, Prandtl, Pecklet,...), geometry of the contact surface and thermodynamic and transport properties of the fluid (i.e. water-steam). Some of the correlation parameters strongly depend on the experimentation and parameter adjusting phase of the modelling work. See [10].

In the development of experimental correlations classes for the heat transfer coefficients *sliding modes* have appeared with some frequency around the phase boundaries of water/steam CVs. Those phenomena are manifested with more frequency when CVs pass from subcooled (region 1 in IAPWS-IF97 standard for water/steam properties, [14]) to saturated (region 4 in IAPWS-IF97), due to two reasons: first, is the existence of discontinuities in the heat transfer coefficients in the

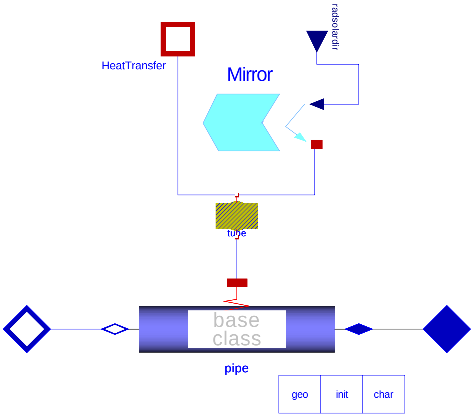

Figure 5: PTC Modelica model.

limit boundary between water and walls; second, is the opposite gradients in the state velocity vectors present around the phase change boundaries. To avoid those cases in which *chattering* causes troubles in the simulation, another polymorphic evaporator model has been developed, in which the subcooled and saturated regions of water/steam pipe are replaced by an equivalent Moving Boundary Model (MBM) [7]. Figure 6 shows this mixed discretized and MBM model for the complete DISS plant, where the MBM component has been designed with ThermoFluid interfaces to be connected with the rest of components.

Although the mixed model lowers the likelihood of finding *chattering* in the integration process, it is theoretically less accurate; and experimentally it is harder to find consistent DAE initial conditions and the validity range of the model is more limited than that of the fully discretized one.

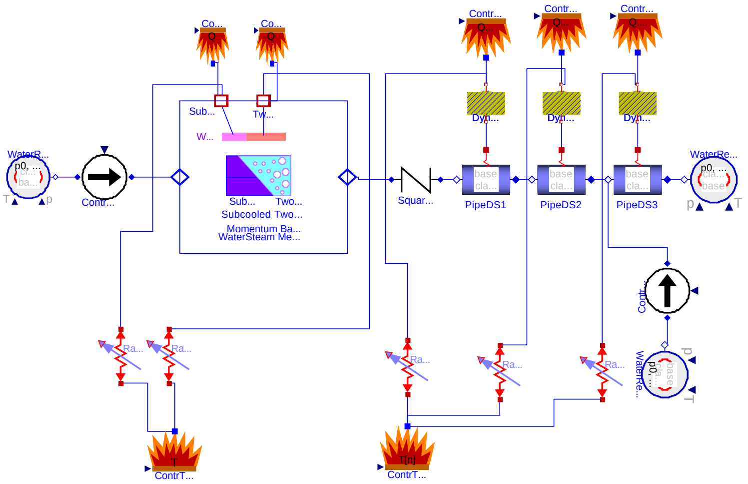

Figure 6: Mixed Moving Boundary and Discretized model of the DISS facility.

With the help of *replaceable/redeclare* constructs and the *choices annotations* ([8], [4]), switching between fully discretized and mixed MBM-discretized models at instantiation time simplifies the modelling work.

3.2.3 Thermo-Hydraulic boundary conditions

When the FVM is applied in thermo-hydraulic modelling, components to define boundary conditions (b.c.) to the original PDE formulated are necessary to close the system of equations. This boundary conditions are implemented in ThermoFluid library by means of reservoirs components, in package *ThermoFluid.PartialComponents.Reservoirs*.

The boundary conditions are defined by reservoirs components that represent pressure, specific enthalpy and temperature b.c. In cases of one-phase fluid (pressure,temperature) pair is selected, and in two-phase fluid the (pressure, specific enthalpy) pair is selected.

4 Simulation and Experimental Validation

In this section the results of a simulation are shown and compared with the corresponding experimental values for some of the variables measured in the actual plant. The experiment was conducted on 1 of April of 2001, starting 9:00 AM and lasting 6 hours and 40 minutes (24000 s.). At which point the DISS plant was forced to the next boundary conditions shown in the top two graphs, shown in figure 7.

In the top graph, the boundary conditions for inlet mass flow rates for the row (mdot_in) and for the injector for the PTC number 11 (mdot_inj_C11) are represented. In the next graph, the boundary condition direct solar irradiance (Solar_Radiation) is shown. From the third to fifth graphs, the measured (MeasuredToutCXX) and simulated (SimulatedToutCXX) outlet temperatures from PTCs

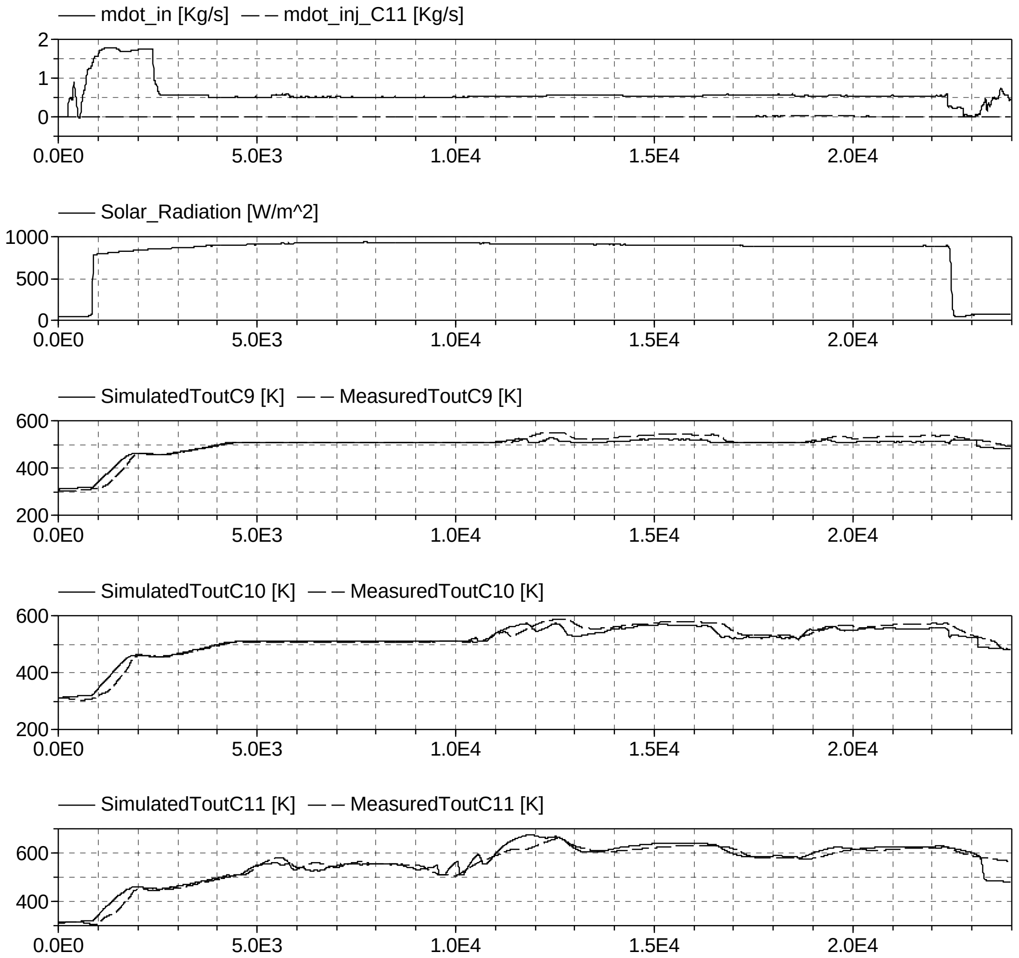

Figure 7: Simulation results for the experiment realized the day 01 of April of 2001. The model is forced to the boundary conditions measured from the experiments.

nine, ten and eleven are shown. The measured variables are depicted in dashed lines as the simulated in continuous lines.

It can be observed that there is a visible difference in the PTC 9 outlet between the experimental and simulated data when superheating appears. This disagreement is augmented due to the fact that a minimum energy difference for the fluid in the twophase-superheating boundary is reflected in a major temperature differences.

In the case of outlet temperature in PTC 10 and 11, a better agreement between experimental and simulated values can be observed. Although in the time intervals in which superheating appears at the outlet of both PTCs a major difference between simulation and experiment can be observed, the dynamic response is similar in both cases. Then, for control purposes the models can be regarded as valid, although a better calibration would be wellcome. For simulation purposes, the calibration work must be refined in the future.

5 Concluding remarks and Ongoing work

This article shows the development of a dynamic model for the CIEMAT's DISS facility using object oriented modelling methodology. The major part of the components are based in the ThermoFluid framework for thermo-hydraulic modelling. The DISS components and main operation principles have been described. For the main components, the modelling hypotheses and the composition Modelica diagrams developed with the Dymola tool have been presented. References to the underlying physical phenomena have been made in these composition diagrams, without entering into detail of quantitatively describing them through differential and algebraic equations; instead, the basic bibliography and the ThermoFluid classes that implements them have been referenced. Finally, a simulation of the system is executed with the boundary conditions of a experiment. Some temperature results of the model simulation are represented with the corresponding experimental measured values. The graphs show that the differences between the experiments results and predicted values from the model are relatively small.

The ongoing work to develop consists in refining the main models parameter calibration based on the experimental results of the actual plant. In this work, the validation of empirical correlations for heat transfer and pressure loss will be an important issue.

The final aim is to develop control and automatic operation systems that would help this type of plants operate in the most autonomous way and in spite of large disturbances. Automatic start-up and shutdowns of the plants is one of the main objectives in this direction.

Acknowledgements

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