Mathematical and Computer Modelling of Dynamical Systems
Vol. 00, No. 00, Month 200x, 1–11

Object Oriented Modelling and Simulation of Parabolic Trough Collectors with Modelica[◇]

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The design of advanced control systems to optimize the overall performance of parabolic trough collectors solar plants with direct steam generation is today a high-priority line of research. This paper presents the main development guidelines for dynamic models for use in simulation and control system design for such plants. The models are based in the *ThermoFluid* thermo-hydraulic modelling framework, developed with the *Modelica* object oriented modelling language. The paper focusses on the DISS experimental solar plant, located at the Plataforma Solar de Almería-CIEMAT (South-East Spain). The main plant operating modes are summarized, as well as the principal components modelled and modelling assumptions. Simulation results of a representative real experiment are shown, in which the values predicted by the model are compared to the real measurements and discussed.

Keywords: object-oriented modelling, dynamic, thermo-fluid, two-phase flow, parabolic trough collectors.

1. Introduction

Electricity production using solar thermal energy is currently one of the main research areas in the field of renewable energies, these systems are characterized by the need of reliable control systems aimed at maintaining desired operating conditions in the face of changes in solar radiation, which is the main source of energy [16], [17], [18]. A new prototype of solar systems with parabolic trough collectors (PTC) has been built at the Plataforma Solar de Almería (South-East Spain), a division of the CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas - *Research Centre for Energy, Environment and Technology*), a dependency of the Spanish Ministry of Science and Education. This solar thermal plant, financed by EC (European Commission)-Joule contract JOR3-CT98-0277 (1998-2001), is called the DISS (DIrect Solar Steam), because its main concern is to research in the direct steam generation process in the parabolic trough solar collector field under real solar conditions, and is used in this paper as a test-bed plant for developing dynamic models aimed at designing automatic control schemes for optimized overall performance. The system (figure 1) is composed of one 500-m row of eleven PTCs, working as a 1 MW_t thermal power plant. A joint project between CIEMAT, 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 this kind of plant.

This paper focusses on thermo-hydraulic PTC modelling issues (see e.g. [3] for a review of thermo-hydraulic modelling of power generation processes), where the developed model will be used in the design of hybrid model predictive control and intelligent control schemes to optimize plant performance as an extension of the work presented in [16], 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. Due to the fact that the main phenomenon of interest is the thermofluid dynamics, the object oriented Modelica language [11] has been used to develop these models with the Dymola tool [4]. Within this modelling language the *ThermoFluid* library [15], [5] is a framework over which develop own libraries and final component models ready to be instantiated as components for simulations.

[◇] This paper was presented at 5th MATHMOD International Conference, Vienna, Austria, 2006.
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Mathematical and Computer Modelling of Dynamical Systems
ISSN: 1387-3954 print/ISSN 1744-5051 online © 200x Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/1387395YYxxxxxxxx

Some attempts have been made at the modelling of storage systems for solar power plants with distributed collectors, using a heat transfer fluid (HTF) in one-phase (e.g. [14], [7]). The Modelica library DissDyn is developed in [9] for the study of the two-phase flow transient behaviour inside the absorber tubes of such plants. This paper focuses on the use of test signals for disturbances in solar irradiation to acquire important information on the fluid loads in the field separator and drainage system. It is shown that these loads can be significantly reduced by adding feed-forward control schemes.

The work presented in this paper deals with the main lines of object-oriented mathematical dynamic model development of the PTC components in the DISS row. The main differences from [9] are:

- The base component is the control volume (CV), modelled as a class in which mass, energy and momentum conservation equations are taken into account. There are two different CVs in which both mass and energy are conserved, or either momentum. In addition, exist predefined usage rules for connecting them. All the classes constituting the DISS row are generated from the interconnection of these components, which are developed based on the *Thermofluid* framework [15].
- The Finite Volume Method [12] is used for the spatial independent variable discretization.
- The thermodynamic properties of the medium used in this work are those of the IAPWS-IF97 standard [20], which is currently the most precise reference for their calculation.
- Several experimental correlations developed at CIEMAT were used for calculating energy flux to the ambient [22].
- The results presented are for the DISS row model working in *once-through* mode under real experimental conditions.

Figure 1. DISS facility at Plataforma Solar de Almería (Southeastern Spain).

2. Basic DISS Facility components and operating procedures

This section gives an overview of the basic DISS plant components and operating procedures. A schematic diagram in figure 2 shows the most important components.

There are three main different operating configurations in the DISS facility, designed for studying thermo-hydraulic behaviour and system performance under real working conditions [6], [17]: the once-through, recirculation and injection modes (figure 3). In all of them operation is based on the concentration of incoming direct solar radiation onto the absorber tube located in the geometric focal line of a parabolic-trough mirror. As the sun position changes during the day, each PTC has to modify its orientation in real time tracking the solar radiation vector. The absorber tube in each PTC acts as an energy exchanger, receiving solar energy and transferring it to an HTF medium in a thermo-hydraulic circuit. The HTF used in conventional PTCs solar plants is thermal oil, which presents major drawbacks with respect to the water-steam medium used in the DISS facility, as explained in [22].

In the once-through mode, feed water is preheated, evaporated, and converted into superheated steam as it circulates from the inlet to the outlet of the collector row. This configuration requires the lowest investment costs and engineering complexity, although controllability problems and instabilities during operation may appear. At nominal operating conditions, the systems works as a distributed once-through boiler fed with subcooled water at the inlet, and the fluid at the outlet is superheated steam.

In injection mode, water is injected at several different points along the row of collectors, so the system works as a once-through evaporator in which an injectors arrangement helps control spatial temperature distribution along the row. Although with this system better controllability and less instabilities can be obtained, the measurement system necessary to implement the control scheme designed for this mode did not work properly during experiments [23], [17], and its complexity and cost would have resulted in this operating mode being discarded in future developments. Moreover, this operation mode requires a higher investment.

In the recirculation mode, which is the most conservative of the three, a water-steam separator is installed at the end of the evaporator section of the collector loop. More water feeds the evaporator than can be evaporated. In the intermediate separator the excess water is recirculated to the collector loop inlet, where it is mixed with preheated water. The excess water in the evaporator section guarantees good wetting of the absorber tubes and makes stratification impossible. The steam produced is separated from the water by the separator and fed into the inlet of the superheating section. This type of system is highly controllable, but the excess water that must be recirculated, the intermediate steam separator and the recirculation pump increase the system parasitic load. The investment in this system is intermediate between the other two.

Therefore, in addition to the PTCs, the facility is composed of the following components:

- Water-steam separator. Used only in *recirculation*.
- Pumps. Feedwater pumps subcool water entering the row and the recirculation pump drains saturated water from water-steam separator.
- Injectors. Actuators that control temperature by injection of subcooled water from the injection line.
- Valves. Allow the system to be configured in any of the three main operation modes and for control purposes.

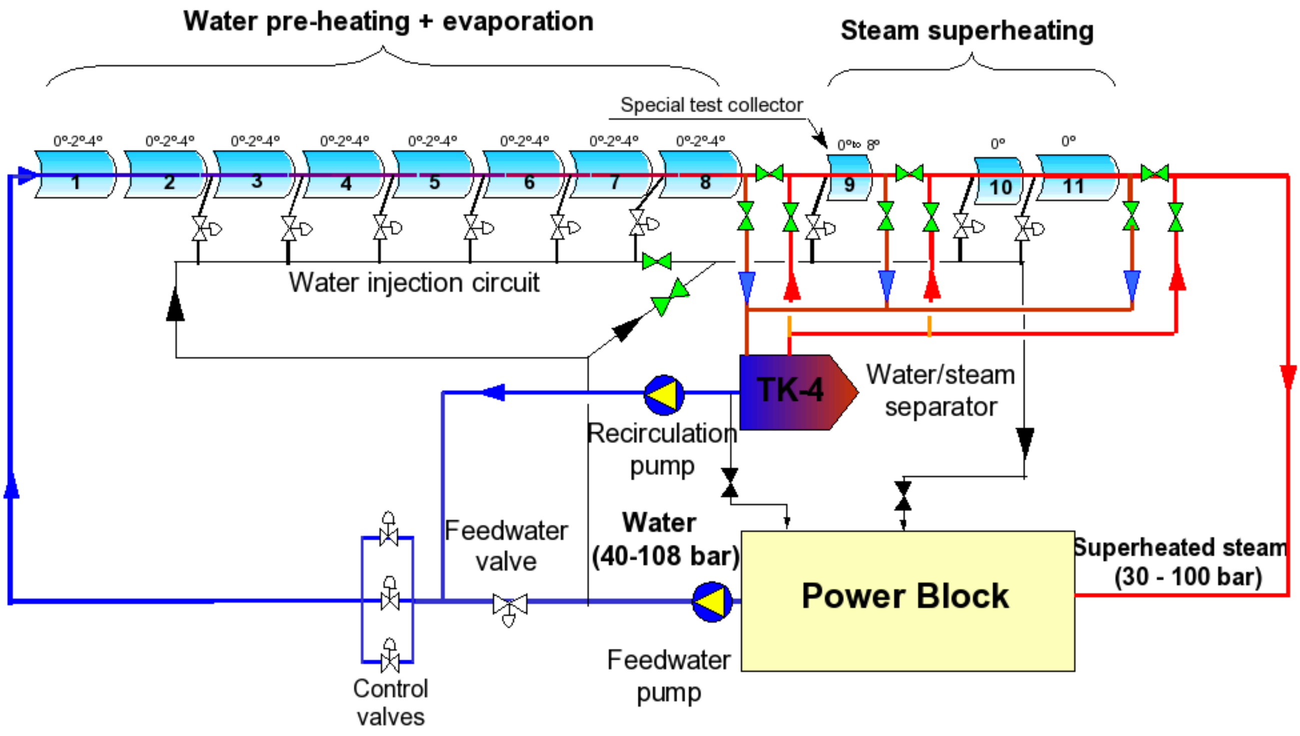

Figure 2. Schematic diagram of DISS facility at PSA

- Power Block. This component represents any possible load process consuming the regulated outlet of thermal power from the plant. In this case, to save water during the experiments, the current implementation returns the thermodynamic state of the outlet superheated steam to subcooled liquid and pumped back in by feedwater pump.

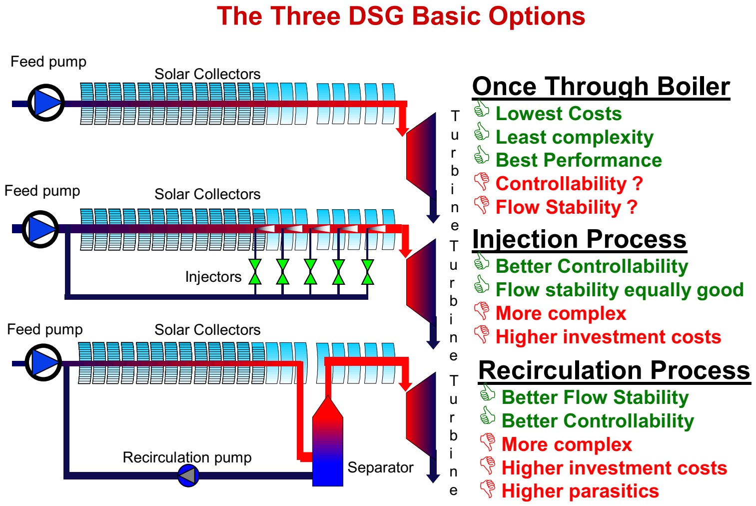

Figure 3. DISS plant operational modes

The main interest is in recirculation mode, although more research must be done on the once-through mode, for which modelling and simulation tools will be essential. In all cases, the superheated steam flow temperature at the outlet must be controlled. Control of the facility has been one of the main CIEMAT efforts [16], although the lack of robust dynamic models for control is a major obstacle in the development of control systems.

The modelling work presented in this paper focuses on the once-through configuration for two reasons. First, the process is not observable by means of the sensors currently installed in the facility. It is not possible to measure/estimate specific enthalpy or mass fractions in transients experiments in the two-phase sections, which at some points in operation occupy up to 50% of the its length. Secondly, it is in this configuration where there is supposedly the most disagreement between the model and experimental data. So any other configuration modelled with components validated in once-through, should show closer agreement with experimental measurements.

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

3. Object Oriented Modelling of DISS

This paper will concentrate on modelling the thermo-hydraulic part of the system, and will not mention the rest of the remaining subsystems (pneumatic, mechatronic, etc.) needed to maintain proper instantaneous orientation of the PTC group, and assumes a known radiation power input in the absorber pipe reflected by the parabolic-trough mirrors. For a detailed explanation of these subsystems see [22] and [21].

As the main phenomenon of interest is the thermofluid dynamics, the object oriented Modelica language [11] was used to develop these models with the Dymola tool [4] using the Modelica-*ThermoFluid* library [15], [5], a framework over which own libraries can be developed and final component models are ready to be instantiated as simulation components. 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. In [14], another different base library, the TechThermo library, is used for simulating a storage system for solar plants with distributed collectors using oil as the HTF medium.

The work analyzes each of the components in the thermo-hydraulic water-steam circuit and explains the modelling assumptions, attempting to justify each as they are oriented to achieve a DAE system index for the complete model that is not very high by symbolic manipulation with the Dymola tool to minimize the number of non-linear algebraic loops. Therefore, all the components are classified, using the modelling derived from the Finite Volume Method (FVM) [12], 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. Strictly speaking, this methodology breaks up first model sequencing to design the control system based on this model. But it helps simplify the model design and enhances the numerical behaviour of the whole system modelled in the simulation stage without a significant loss of accuracy.

Because the internal implementation of components may vary depending on the modelling hypotheses, polymorphism and the Modelica language constructs have been extensively used for classes and component parameterization and specifically applied in PTC models.

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

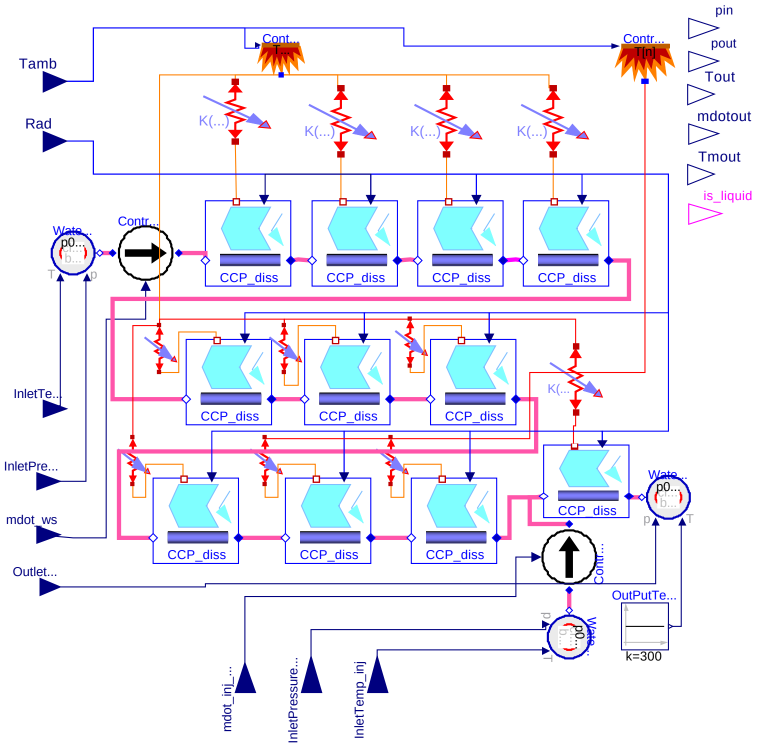

Figure 4. Modelica model of DISS plant in *once-trough* configuration.

After compiling the model of figure 4 using Dymola tool, a set of nonlinear differential equations parameterized as shown in equation 1 are obtained

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x},\mathbf{u},\mathbf{p}) \qquad (1)$$
$$\mathbf{y} = \mathbf{G}(\mathbf{x},\mathbf{u},\mathbf{p})$$

where:

- $\mathbf{p} = (f_f, \alpha_0, \alpha_1, \alpha_2, \eta_{0,1}, n_1, \ldots \eta_{0,11}, n_{11})^\intercal$ is the vector with 26 parameters that are not completely determined from first principles and are subjected to uncertainty.
- $\mathbf{x} = (p_i, h_i, T_{mi})^\intercal,\ \ i = 1 \ldots N_{CV},\ \ N_{CV} = \sum_{i=1}^{i=11} n_i$. Is the vector of state variables of dimension $dim(\mathbf{x}) = 3N_{CV}$, where N_{CV} is the number of CVs in the complete model of the DISS row. It is constituted by the pressures p_i and specific enthalpies h_i of each volume, and the temperature of each section of absorber tube T_{mi} in thermo contact with each CV.
- $\mathbf{u} = (p_e, T_e, I, T_{amb}, p_{iny}, T_{iny}, \dot{m}_{fm}, \dot{m}_{iny}, p_s)^\intercal$. Is the vector of boundary conditions constituted by: row input pressure, temperature of the water at the row inlet, direct solar radiation normal to the PTC, ambient temperature, pressure and temperature at the entrance of the injector, mass flow at the field inlet, mass flow at the injector input and outlet steam pressure. From the control viewpoint, the mass flows are manipulated variables to control the outlet temperature of the last collector and the outlet pressure is a controlled variable.
- $\mathbf{y}$. Is the vector of output variables of the models, some of which are assigned to the output connectors of the model in figure 4.

3.1. *ThermoFluid* ***usage***

The thermodynamics behaviour is mainly expected to be predicted by the models, so the *ThermoFluid* base class for steady state formulation of the momentum balance is used. The time scales selected for the thermodynamics 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 the steady-state momentum balance statement. The modelling methodology used for class design was: *if there is any class in ThermoFluid that implements the physical phenomenon to be modelled, use it with the corresponding parameterization. If not, design the classes using inheritance from the partial higher level classes in ThermoFluid; otherwise use ThermoFluid interfaces and base classes and develop them expressing missing behaviour in differential and algebraic equations from first principles*.

3.2. *Designed Classes*

In the following subsections, the most important components of the models are described and the modelling hypotheses are explained and justified.

3.2.1. Pumps and Injectors. For this kind of active FM [15], the authors decided to make a simplifying assumption based on their experience in PTC control with thermal oil as the medium, as in the case of the CIEMAT Acurex field [2], and water-steam as the medium in the DISS facility [22], [16], [18]. This assumption is that the water pumps are controlled by a cascade control scheme [1] with a local control loop with much faster dynamics than the rest of the thermo-hydraulic system. This assumption has been experimentally validated in blowers and water pumps, and helps simplify these component models until they can be modelled as steady-state quasi-ideal mass flow rate generators. This approximation avoids the time-consuming work of fitting the nonlinear multivariate pump and injector curves. 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 assigned to the model by a connector, as shown in Figure 4.

3.2.2. Parabolic Trough Collectors. The PTC is the most important component in the facility. Its function is to direct the beam solar irradiance incident on the mirror to the absorber tube, for which the manufacturing process makes use of advanced material sciences and technologies to minimize the power loss on the absorber tube. [8] and [22], analyse the solar energy flows into the absorber.

Figure 5 shows the main components of a PTC, enumerating the following:

- Parabolic-trough mirror surface: Reflects the direct solar radiation incident on the focal line of the mirror.
- Metal absorber pipe: Absorbs most of the energy reflected by the mirror.
- Energy loss to the environment by conduction-convection and radiation.
- HTF medium model: In the case in hand, this medium is water-steam.

- Distributed CV, with discretization level n in which mass, energy and momentum are conserved.

For modelling purposes, this component could be considered a heat exchanger with only one pipe with water and/or steam as the media fluid, and a circular wall for thermal exchange with the fluid. This heat exchanger is fed by solar energy entering through the outer perimeter of the wall and, at the same time, some energy flow leave through this outer perimeter by conduction-convection and radiation.

The water/steam pipe is 50 m long, and under normal operating conditions, the inlet/outlet flow may be in any of the three states water, two-phase mix of saturated liquid and vapour, or superheated steam. This depends on the position of the PTC in the row as well as the incident solar radiation on it.

Thus the dynamic behaviour of each PTC varies along the DISS row depending on the thermodynamics and transport state of the water/steam in each PTC. With the configuration shown in Figure 5, most of the length of the PTC is fully discretized in n CVs, in which mass, energy, and momentum balances are given. Momentum conservation is stated in CVs staggered with regard to mass and energy balance CVs (see [12], [19] and [15]). The number of CVs, n, is a trade-off between accuracy and computing cost, so for control purposes, the final choice is the minimum n that models dominant dynamics. The current values used are in the interval $[2,5]$ for each PTC. The wall discretization level is the same.

To solve the PDE system stated from balance equations, *ThermoFluid* provides partial classes [15] in which the discretization with the Finite Volume Method (FVM) [12] is applied. One of these classes is *ThermoFluid.PartialComponents...Volume2PortDS_pT*, which implements these mass, energy and static momentum conservation equations in a staggered grid formed by n subvolumes. Final use classes, *ThermoFluid.Components.HeatFlow.Walls*, implement energy conservation in distributed solids.

To close the equation system, the heat transfer coefficient for the water-steam flow and the solid media must be entered. This coefficient depends on heat transfer correlations using adimensional fluid numbers (Reynolds, 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 adjustment stage of modelling [13].

In developing experimental correlation classes for the heat transfer coefficients, *sliding modes* have appeared with some frequency around the water/steam-CV phase boundaries . Those phenomena are more frequent when CVs go from subcooled (Region 1 in IAPWS-IF97 standard for water/steam properties, [20])) to saturated (Region 4 in IAPWS-IF97), for two reasons: First, the existence of discontinuities in the heat transfer coefficients on the boundary between water and walls, and second, the opposite gradients in the state velocity vectors present around the phase-change boundaries. To avoid chattering in the simulation, another polymorphic evaporator model has been developed, in which the subcooled and saturated regions of the water/steam pipe are replaced by an equivalent Moving Boundary Model (MBM) [10]. Figure 6 shows this mixed discretized and MBM model for the complete DISS plant, where the MBM component was designed using ThermoFluid interfaces for connection to the rest of the components.

Although the mixed model reduces the likelihood of finding *chattering* during integration, it is theoretically less

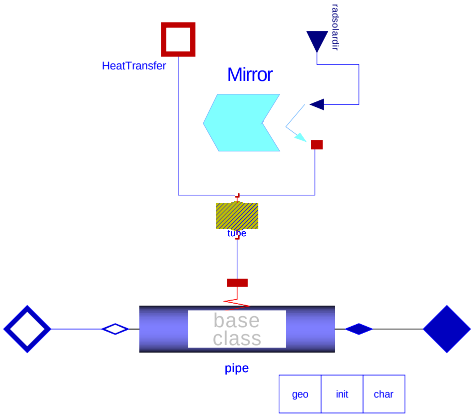

Figure 5. PTC Modelica model.

accurate, it is harder to find consistent initial DAE conditions experimentally and the model's range of validity is more limited than that of the fully discretized one.

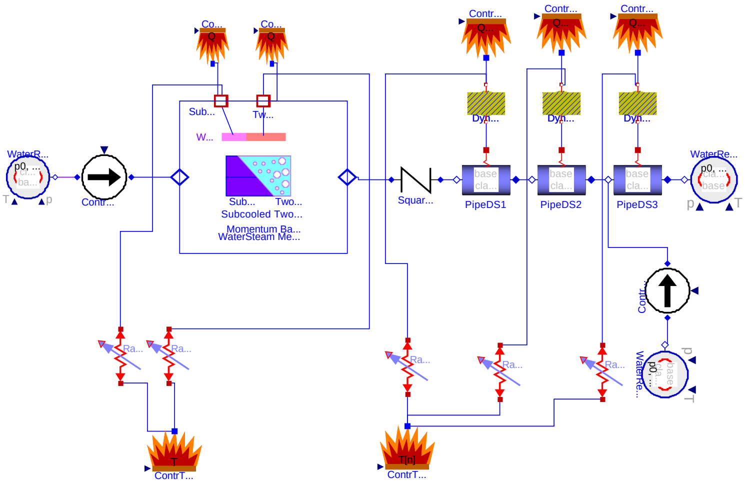

Figure 6. Mixed Moving Boundary and Discretized model of the DISS facility.

With the help of *replaceable/redeclare* constructs and the *choices annotations* [11], [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 defining the original PDE boundary conditions are necessary to close the system of equations. These boundary conditions are implemented in the *ThermoFluid* library by means of reservoir components, in the *PartialComponents.Reservoirs.* subpackage.

The boundary conditions are defined by reservoir components for pressure, specific enthalpy and temperature boundary conditions. For one-phase flow, the (pressure, temperature) pair is selected, and in two-phase flow the (pressure, specific enthalpy) pair is selected.

4. Simulation and Experimental Validation

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

To arrive at the results presented in this section, a number of assumptions were made such that the initial number of parameters in Equation (1) would be reduced from 26 to 8, as enumerated in Table 1, containing the model parameters resulting from the simplification.

These simplifying assumptions are:

- A constant number n of CVs per collector is considered, independent of the state.
- Assuming the same peak optical efficiency for all the collectors with fluid in the same thermodynamical state: water ($\eta_{0,sc}$), two-phase ($\eta_{0,sat}$) and superheated ($\eta_{0,sh}$).
- The same constant friction factor f_f is assigned to all the PTCs.
- A unique absorber tube to fluid heat transfer coefficient for each thermodynamical state: water (α_0), two-phase (α_1) and superheated (α_2).

The parameter calibration process was done in two steps:

Parameter	Meaning	SI units
n	Number of CV per PTC of 50m length	$[-]$
$\eta_{0,sc}$	Peak optical efficiency of PTC 1 and 2	$[-]$
$\eta_{0,sat}$	Peak optical efficiency of PTC 3 to 9	$[-]$
$\eta_{0,sh}$	Peak optical efficiency of PTC 10 to 11	$[-]$
f_f	Moody friction factor	$[-]$
α_0	Heat transfer coefficient for water	W/m^2K
α_1	Heat transfer coefficient for two-phase flow	W/m^2K
α_2	Heat transfer coefficient for superheated flow	W/m^2K

Table 1. Parameters of the model.

(i) Estimation of the starting values of the parameters, from previous work in the facility and knowledge of physics [22].
(ii) Application of multicriteria optimization identification techniques using experimental data, [4].

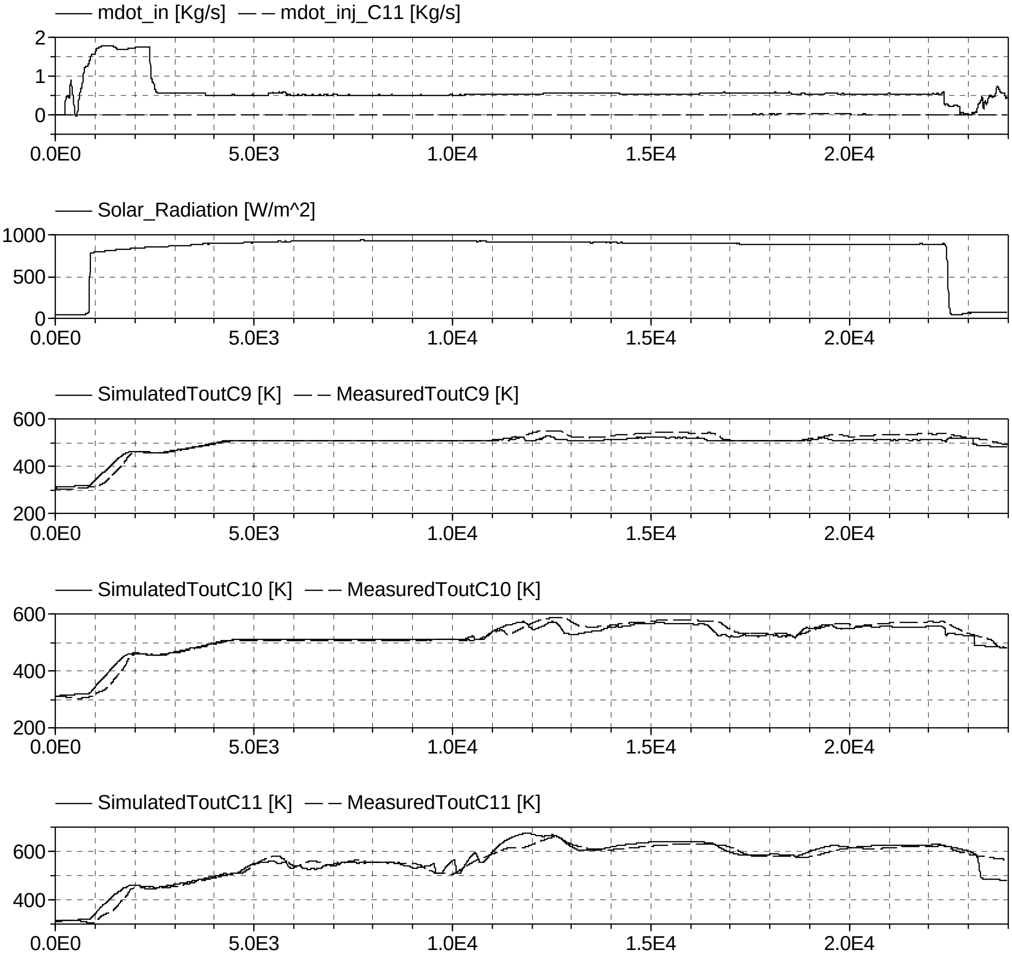

Figure 7. Simulation results for the experiment performed on April 01, 2001. The model is forced to the boundary conditions measured from the experiments.

The top graph shows the boundary conditions for row inlet mass flow rates (mdot_in) and PTC injector number 11 (mdot_inj_C11). The second graph shows the boundary conditions for direct solar irradiance (Solar_Radiation). The third to fifth graphs show the measured (MeasuredToutCXX) and simulated (SimulatedToutCXX) outlet temperatures in PTCs nine, ten and eleven. Dashed lines indicate the measured variables and continuous lines are the simulated values.

It may be observed how during operation start-up, all the PTC outlet temperatures are close to the experimental data. There is a kind of unmodelled transport delay in which the time it takes for the saturation state to be reached at the outlet of each PTC depends on its position in the row. The saturation temperature of each one can easily be identified. Once the PTCs are saturated, modelling errors are due to the differences between the saturation temperatures calculated using the standard IAPWS-IF97 [20] and the measured pressures and temperatures.

From left to right on the abscissa, Collectors 11 and 10 reach the superheating state, as well as Collector 9 at several different time intervals. The difference between simulated and real data is widest for Collector 9, because of small internal energy differences in a control volume near the boundary of the phase-change between saturation and superheating, where the temperature differences are high.

It may be seen how the errors increase during superheating and along the collector row, because the collectors are connected in series and the errors accumulate as a consequence of having used the state variables calculated for each collector as boundary conditions for the following PTC. To decrease these modelling errors, during the identification stage, calibration was sequentially guided from the first PTC to the last. Once the initial estimation of the parameters was achieved, a final optimization was performed until arriving at the results presented.

5. Concluding remarks and ongoing work

This article describes the development of a dynamic model for the CIEMAT DISS facility using the object oriented modelling methodology. Most of the components are based on the *ThermoFluid* framework for thermo-hydraulic modelling. The DISS components and main operating principles have been described. For the main components, the modelling hypotheses and Modelica composition diagrams developed with the Dymola tool have been presented. References to the underlying physical phenomena have been made in differential and algebraic equations in these composition diagrams, without entering into the details of quantitative description. Instead, the basic bibliography and the *ThermoFluid* classes that implement them have been referenced. Finally, the system is simulated with the experimental boundary conditions. Some model simulation temperatures are shown with the corresponding experimental measurements. The graphs show that the differences between the experiment results and predicted values from the model are relatively small.

Future work to be developed consists of refining the main model parameter calibration based on the experimental results of the actual plant. In this work, the empirical validation of heat transfer and pressure loss correlations will be an important issue.

The final aim is to develop control and automatic operating systems that would help this type of plant operate as autonomously as possible in spite of significant disturbances. Automatic plant start-up and shutdown is one of the main targets in this direction.

Acknowledgements

This work was financed by the CIEMAT, European Union funds for research projects: DISS-Phase II (E.U. DGXII JOULE JOR3-CT98-0277), EUROTROUGH - II (E.U. DGXII JOULE ERK6-CT1999-00018); and CICYT-FEDER funds (projects DPI2004-07444-C04-04 and DPI2004-01804). This work was also performed within the scope of the specific collaboration agreement between the CIEMAT and the University of Almería Automatic Control, Electronics and Robotics (TEP197) research group, titled ”Development of Control Systems and Tools for Thermosolar Plants”.

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