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Abstract: Direct Steam Generation (DSG) concentrated solar plants are promising but complex power systems. This latter feature originates both from the variety of physical phenomena and the dynamic nature of the boundary conditions at play during plant operation. A representative yet computationally efficient numerical simulator is a valuable tool to assist engineers in the proper design, control and operation of such specific water-steam cycle. The present communication reports on the development of a multi-domain dynamic model representing a DSG plant. To do so, we followed a code-coupling approach and relied on the domain-decomposition paradigm. More specifically, we built three sub-models respectively in the thermal-hydraulic, the optical and the control-command domains and coupled them through an in-house co-simulation platform called PEGASE. We used the CATHARE system code to solve the thermal-hydraulic problem and the more generalist DYMOLA software to model the convective and radiative heat exchanges within the solar receiver. As an example, we then applicate the simulator to elaborate an efficient controller for the steam separator level.

Keywords*:* Concentrated Solar Power (CSP), Direct Steam Generation (DSG), dynamic modelling, co-simulation, two-phase flow, control-command.

1. INTRODUCTION

Nowadays, one of the solutions considered in order to face the issue of global warming and to move towards a carbon neutral society relies on the use of solar energy as a renewable and bountiful primary source. And, if photovoltaic technologies account for a large part in the solar energy market, recent years have witnessed the growth of non-concentrated and concentrated solar thermal technologies. Among them, Concentrated Solar Power technology (CSP) which uses the optical concentration of direct solar irradiation to generate high pressure and temperature steam has become a promising approach reaching 4.9 GWe of installed capacity by the end of 2015 [HeliosCSP].

In general, solar systems are designed to be able to operate despite the variability of power input related for example to sunrise, sunset, clouds, etc. This is no easy task for DSG CSP plants, not least because of the complexity of the two-phase flow thermal-hydraulic phenomena occurring inside the absorber tubes. In such a context, numerical simulation tools are an effective means to better handle the design and operation of CSP plants. These can for instance be applied to the design, the verification and the validation of advanced and robust control systems. More generally, these tools may bring to light full understanding of the system's response to some proposed perturbation at a very competitive cost.

The French Alternative Energies and Atomic Energy Commission (CEA), operates parabolic trough and linear Fresnel prototypes in Cadarache, France. Our research group has been involved in the design of the aforementioned prototypes. The present paper reports on the development of a multi-domain dynamic simulator.

Generalist simulation environments such as DYMOLA, MATLAB-SIMULINK or AMESIM all claim to be suitable for multi-domain systems analysis. However, solving water-steam two-phase flows at the system scale is generally problematic in terms of numerical robustness and efficiency for such simulation software. Moreover, available modelling libraries often rely on the homogeneous flow model which is a too coarse assumption for the phenomena of interest. On the other hand, the nuclear sector has, these past decades, developed and validated several computational codes to deal with system transients for two-phase flows in one-dimensional space. Examples of such codes are RELAP, TRACE, and CATHARE [Geffraye et al., 2011]. However, such codes are difficult to develop beyond their initial physical domain. It would for instance be challenging to model the convective and radiative heat fluxes within a solar receiver by using these codes. We therefore believe that code-coupling is an interesting approach to secure the way towards a full scope dynamic simulator of a CSP plant. To the authors' knowledge, this approach is rather new to the solar community.

The outline of our paper is the following. Section 2 describes our coupling approach as well as the tools we used for implementation. In section 3, we present the models we have developed and an application is then detailed in section 4. Section 5 is a discussion and perspective chapter, while the conclusions of our study are presented in section 6.

2. CODE-COUPLING APPROACH AND IMPLEMENTATION

2.1 Code-coupling approach

Code-coupling can be divided into two main groups.

In the **domain overlapping approach**, one "system" code solves the whole system while "specialized" codes also compute the overlapping parts of the domain. The coupling occurs when the results of the "system" code are corrected by the solutions proposed by the "specialized" codes. This is a popular solution to deal with 1D/3D code coupling and to cope with numerical instability issues.

In the **domain decomposition approach**, non-overlapping geometrical and physical domains are defined and assigned to "specialized" codes. The coupling is realized through exchanges of values along the sub-domains interfaces.

In the present work, we selected a domain decomposition approach. Three sub-models, respectively in the thermal-hydraulic, the thermal and the control-command domains were defined to represent a portion of a CSP plant. The subsequent section describes how these sub-models are handled during the coupling and the next one will describe the co-simulation execution scheme.

2.2 Implementation

Code-coupling is implemented using an in-house framework named PEGASE. PEGASE is based on a low-level platform developed by the L3S company [L3S, 2017] which enables multi-models simulation based on the FMI 2.0 co-simulation standard [Blochwitz et al., 2012]. PEGASE was designed to ease the realization of simple Co-Simulation or more complex optimal control applications.

In the PEGASE framework, each sub-model is controllable through a C++ class deriving from a common "mother" class. The supported methods allow for managing the life-cycle of the sub-models (e.g. construction, destruction …), the time advance (e.g. pre- & post-stepping, time-step computation …) and the data exchange through "mutators" and "accessors". Data are exchanged via a common "exchange zone", defined as the concatenation of the outputs of each sub-models.

2.3 Execution scheme

The Co-Simulation execution scheme used for the present application is illustrated in Fig. 1. Each sub-model is simulated individually and data exchanges occur at discrete time instants called communication points. Communication points are periodically distributed along the time axis with an elementary time step **δt**.

For simplicity reasons, we used an explicit time scheme; when not available, input variables at **t + δt** were provided by output variables evaluated at **t**. Despite this choice, the multi-domain simulator remained stable for time steps greater than 10 seconds. However, a time step of 2 seconds was retained considering the fact that larger values are not recommended for the CATHARE code. Thus, the simulated process is approximately 15 times faster than the real process.

2.4 Coupling variables

The coupling between the internal thermal-hydraulic and the thermal solar receiver sub-models was realized by exchanging temperatures (T) and heat fluxes (W) (Fig. 3). The coupling between physical and control-command sub-models is implemented by exchanging sensors and actuators values.

3. MODELLING

3.1 Thermal-hydraulic sub-model

The CATHARE thermal-hydraulic code was used to model a portion of the water-steam cycle of the Fresnel plant. The main features of this model are given hereafter. We choose to model the vaporisation loop of a plant operate in recirculation mode.

Fig. 2 is a schematic view of the thermal-hydraulic sub-model. The model begins at the outlet of the preheater (top left) and ends after the steam-separator tank (top right). The recirculation loop between the liquid part of the separator and the vaporizer is also represented. The model is composed of a collection of 0D and 1D modules based on a two-fields, 6 equations modelling approach. For each elementary cell, the mass, energy and momentum equations are written and specific closure laws are used to define the thermal and mechanical coupling between the two fields.

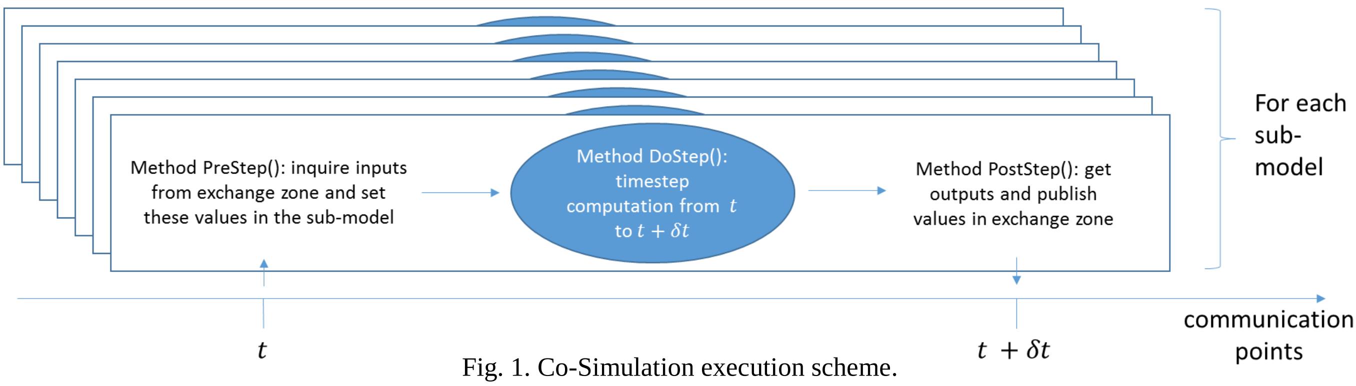

Fig. 1. Co-Simulation execution scheme.

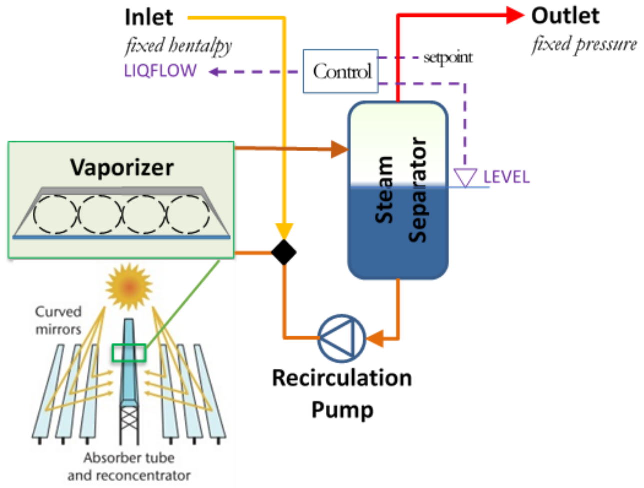

Fig. 2. Schematic view of the thermal-hydraulic sub-model.

3.2 *Optical sub-model*

The optical sub-model has been programmed with the Modelica language, prepared in the DYMOLA environment and encapsulated in a Co-Simulation Functional Mock-up Unit (FMU) in order to ease its processing by the PEGASE framework. We choose a Fresnel trapezoidal type receiver composed of several absorber tubes enclosed in a cavity thermally insulated on the upper face and closed by a window on the lower face (see Fig. 3). The objective of this model is to calculate the thermal efficiency of the receiver in order to compute the thermal power available for the absorber tubes.

The different terms appearing in the model are presented in Fig. 3. However, for space reasons the corresponding equations will not be presented here.

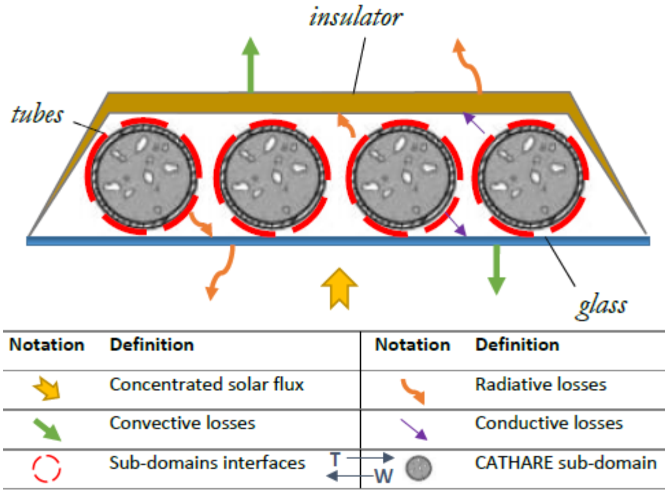

Fig. 3. Layout of a Fresnel Trapezoidal Receiver (FTR).

3.3 *Control-command sub-models*

Control-command sub-models were developed within an integrated “logic” or “causal” graphical model editor available in the PEGASE framework.

A single feedback Proportional-Integral (PI) controller was developed and Fig. 4 shows a screenshot of the corresponding sub-model. In this example, the process variable is the value of the steam separator level (LEVEL) which is provided by the thermal-hydraulic sub-model and compared to the set point. The corresponding error is then processed by the PI controller (only the proportional and the integral actions are considered here) which sets the manipulated variable (the inlet mass flow rate LIQFLOW here) to a suitable value in order to approach the set point. If the steam separator level increases, the inlet mass flow rate is decreased and *vice versa*.

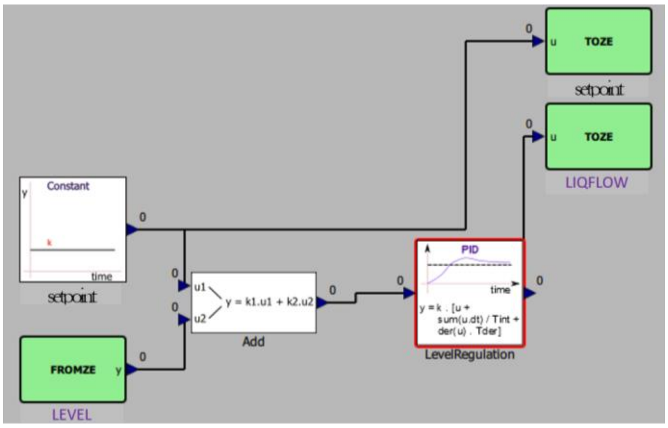

Fig. 4. View of the PI controller sub-model taken from the PEGASE framework.

The tuning of the PI parameters of the controller is discussed later in this paper (see 4.2).

A feedforward plus feedback controller has also been developed. The solution investigated to regulate the steam separator level is to account for the Direct Normal Irradiation (DNI) disturbances in the control strategy. Indeed, for a given value of DNI, it is possible to compute an inlet mass flow rate corresponding to steady state operation and thus stable steam level. Let ($\dot{m}_{stat}$) be the corresponding stable solution. The controller can then be built from ($\dot{m}_{stat}$) corrected by an additional feedback PI controller ($PI_{corrections}$).

$$\dot{m}_{inlet} = \dot{m}_{stat} + PI_{corrections}$$

This control strategy is part of the feedforward plus feedback control strategies mentioned and analysed in [Kumar et al., 2015]. It takes into account a part of the disturbances which affect the plant (in a predictive way). However, feedforward control should be combined with feedback control. Indeed, the role of the feedback controller is to cope with the modelling errors in the computation of the stationary mass flow rate and more generally with unavoidable disturbances.

4. APPLICATIONS OF THE NUMERICAL MODELS

The results described here after aim primarily to illustrate the good operation of the co-simulation process involving the sub-models introduced in section 3 of this paper. It also gives tips and tricks when it comes to designing efficient controllers by using dynamic simulation tools.

4.1 *Co-simulation on a sunny day*

The different models have been co-simulated together and tested for an "ideal" summer day.

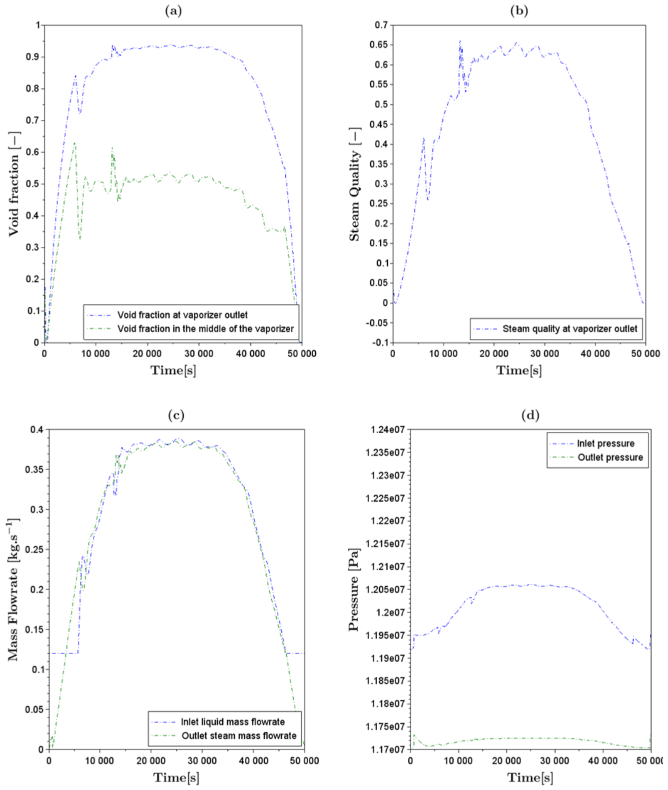

Fig. 5. Excerpts of the fluid thermal-hydraulic properties available from the co-simulation results (time evolutions over one day).

As the fluid is evaporating along the absorber, steam is produced and the void fraction increases. This is what is represented in Fig. 5 (a). It can be noticed that the major part of the mesh volume at vaporizer outlet (about 90%) is occupied by steam. However, Fig. 5 (b) highlights that the steam quality at vaporizer outlet in the middle of the day (t=0s corresponds to 8 a.m.) remains in the desired range mentioned in [Hirsch et al., 2014], i.e. between 60% and 80%.

Fig. 5 (d) gives an idea of the pressure loss occurring in the sub-system in the case of the higher solar heat flux investigated (around 3 bars, i.e. 2.5% of the inlet pressure).

A more formal validation of the numerical results through a cross-comparison with experimental data is expected in the future. In the same way, the input DNI considered here is an ideal one and will be replaced by data coming from on-site measurements.

4.2 *Assessment of the controllability of the system*

The variability of solar resource along with the biphasic issues related to the evaporation of water in DSG power plants are the main arguments which make necessary a control system implementation.

[Valenzuela et al., 2006] points out that the main task of this control system is the provision of constant live steam conditions at the outlet of the solar field for all operating conditions. Complex control strategies should consequently be developed in order to ensure this role.

As a first step, the controllability of the co-simulated system is assessed considering only the regulation of the steam separator level.

Implementation of a single feedback PI controller:

A single feedback PI controller whose structure has been presented in 3.3 has been implemented in the model in order to maintain a stable level in the steam separator. This implementation involves three steps:

- ***Identification of the steam separator level evolution***

Considering a stable operating point, the identification test consists in analysing the level response (process variable) to a step increase of the water mass flow rate at the system inlet (manipulated variable).

In spite of a small fluctuation at the beginning of the step probably due to some dynamic effects, the level response to a step increase of the manipulated variable is clearly unstable (See Fig. 6). Indeed, the stabilization occurring after 6000s corresponds to the saturation of the steam separator level whose maximal value is 2.75 m. As already done by Aurousseau [2016] or Valenzuela *et al* [2006], we identified the steam separator level evolution process as a delayed integrator.

- ***Tuning of the PI parameters***

Nowadays, PID controllers are extensively used in order to regulate industrial processes and numerous relevant methods are available and discussed in the literature when it comes to tune PID parameters [Kumar et al., 2015]. Ziegler and Nichols [1942] suggested two ways to find the optimum parameters for a given installation. Over the years, this methodology has been adapted and modified but it remains one of the simplest and the fastest way to determine relevant values of the three PID constants.

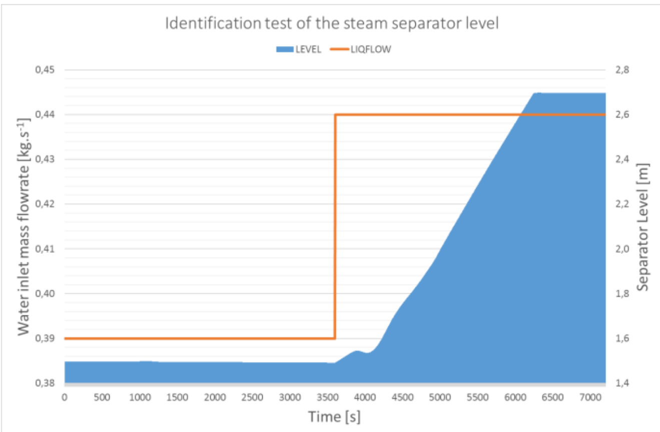

Fig. 6. Steam separator level identification test

The temporal equation of a series PID controller is given in the following equation:

$$u(t) = K_s * \left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt}\right)$$

$u(t)$: Value of the manipulated variable (inlet mass flow rate),

$e(t)$: Difference between the process variable value (steam separator level here) and the set point value,

K_s : Proportional gain of the series PID controller,

T_i: Integral time constant,

T_d: Derivative time constant.

As mentioned above, two methods for tuning a PID controller were suggested by Ziegler and Nichols. One of them takes into account the process response in an open-loop system and the other one considers the closed-loop system [Magnon, 2007]. In the second method, a step change in the set point is made and the proportional gain of the PID controller is then increased while maintaining the integral time constant at infinity and the derivative time constant at zero, until the system undergoes sustained oscillations. When this happens, the critical gain is noted (K_{cr}) as well as the periodicity of the sustained oscillations (T_{cr}).

Then, from Ziegler and Nichols paper, Table 1 can be drawn. The values of the different PID corrective terms are derived according to the values of the two critical values expressed here above and the type of the controller.

Table 1. Tuning of the corrective parameters according to Ziegler and Nichols methodology

Controller	K_s	T_i	T_d
P	0.5 K_{cr}	-	-
PI	0.45 K_{cr}	0.83 T_{cr}	-
PID	0.6 K_{cr}	0.5 T_{cr}	0.125 T_{cr}

In the case of the steam separator level regulation for which a PI controller is implemented, this investigation was carried out. Table 2 gathers the critical values obtained as well as the suggested values for the proportional gain and the integral time constant by the Ziegler-Nichols methodology.

Table 2. Critical values and suggested ones from Ziegler-Nichols methodology

K_{cr}	T_{cr}	$K_{s,ZN}$	$T_{i,ZN}$
0.6	1644 s	0.27	1365 s

- ***Fine-tuning of the PI parameters evaluated***

In a general way, one of the main limitations of Ziegler-Nichols methodology is that the values of the corrective parameters obtained lead to short rise times but relatively high overshoots. This phenomenon can be reduced by decreasing the value of the proportional gain [Magnon, 2007] and increasing the value of the integral time constant. In this respect, a trial and error process has been conducted in order to find better suitable values for the PI parameters. They are given in Table 3.

Table 3. Fine-tuned PI corrective parameters

K_s	T_i
0.2	1800 s

<u>Implementation of a feedforward plus feedback PI controller</u>:

In 3.3, the principle of a feedforward plus feedback PI controller has been developed. The aim of this controller is to combine the estimation (based on the current DNI value) of the water mass flow rate to impose at the inlet of the system in order to get a stationary state, and thus a stable steam separator level. A regular PI feedback corrects this estimation. Thus, the DNI disturbances should be better handle by the controller.

In order to compare the dynamic precision of the two control strategies presented here (single feedback PI controller and feedforward plus feedback PI controller), four indicators well documented in the literature can be used [Vallain 1997]. They are: Integral of Absolute Error (IAE), Integral of Time multiplied by Absolute Error (ITAE), Integral of Square Error (ISE), Integral of Time multiplied by Square Error (ITSE).

$$IAE = \int_0^{tend} |\varepsilon(\tau)|d\tau \quad ITAE = \int_0^{tend} \tau * |\varepsilon(\tau)|d\tau$$

$$ISE = \int_0^{tend} (\varepsilon(\tau))^2 d\tau \quad ITSE = \int_0^{tend} \tau * (\varepsilon(\tau))^2 d\tau$$

The two control strategies have been compared during a simulated ideal sunny day with clear sky (see Fig. 7) and during a 15 min cloud passage. The dynamic criteria mentioned previously are gathered in Table 4 for each situation.

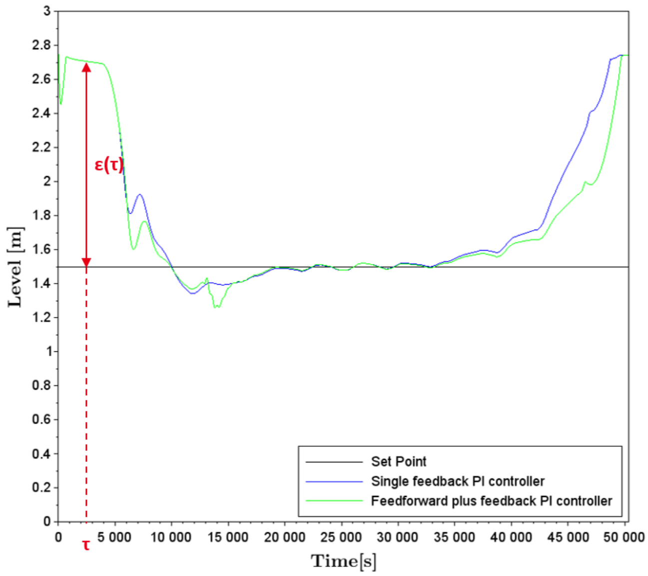

Fig. 7. Comparison of the two control strategies during an ideal sunny day with clear sky (no cloud passage)

Table 4. Comparison of the control strategies during a sunny day with or without a 15 min cloud passage

Control Strategy	IAE	ITAE (.10^6)	ISE	ITSE (.10^6)
Single feedback PI	7900 9461	190 233	6917 8254	156 193
PI with feedforward	6672 7531	139 165	5503 6143	92 110

For both comparisons, the indicators are in favour of the PI controller including the calculation of the stationary mass flow rate. Thus, its response is less nervous and less oscillatory than the one of the single feedback PI controller. The calculation of the stationary mass flow rate enables the controller to better handle the disturbances in the DNI. By adding a supplementary information about the physical behaviour of the system in the architecture of the PI controller, this solution is a natural improvement of the single feedback PI controller.

5. DISCUSSION AND FURTHER DEVELOPMENTS

The thermal-hydraulic sub-model built with the CATHARE code refers to the part of the water-steam cycle surrounding the vaporizer, it is to say, beginning at the preheater outlet and ending at the inlet of the superheater. This model will be extended, in a near future, to encompass the superheater. In the long run, an extension of the model to include the entire primary loop of a DSG plant is foreseen. Moreover, a comparison with a dymola-only model and a validation through a numerical vs. experimental cross-comparison will both be conducted in a near future.

Furthermore, this sub-model will be enhanced to account for the thermal losses to the ambient in the circulating pipes and the thermal inertia effect of these tubes. The addition of these losses would lead to an improved version of the model. Furthermore, as thermal inertia can constitute a way to reduce the sensitivity of a CSP plant to the fluctuations in the solar irradiation [Ruspini et al., 2014], a profitable improvement would be to include this thermal inertia by explicitly adding insulating walls in the circulating pipes modelling instead of considering a simple equivalent thermal resistance.

Other perspectives of the work presented in this paper is to use the co-simulated model in order to: test the interest of PI controller with adaptive parameters for the wide range of working conditions to be considered in a CSP Plant; develop “training simulators” for the operation of plants.

6. CONCLUSIONS

The work summarized in this paper deals with the development of a multi-domain dynamic simulator of DSG concentrated solar power plants. By taking into account the impact of solar irradiation variations over the day, it is expected to provide a sophisticated picture of the behaviour of plants when they face DNI disturbances. To do so, we used a code-coupling approach of the domain decomposition type.

Three sub-models, respectively in the thermal-hydraulic, the thermal and the control-command domains were prepared and coupled using an in-house co-simulation framework called PEGASE. Considering, the thermal-hydraulic sub-model, only a portion of the water-steam cycle has been modelled using the CATHARE code. The coupling with an optical model of a FTR has then been implemented. The setting up of a one-day co-simulation during an ideal sunny day has allowed us to verify the proper functioning of the simulator.

Then, the one-day co-simulation set up enabled us to test several control strategies for the regulation of the steam separator level. PI parameters have been tuned based on the Ziegler-Nichols methodology and fine-tuned through a series of numerical simulations. The interest of the integration of the stationary mass flow rate calculation in the controller has eventually been highlighted.

Nowadays, 6 equations two-fields thermal-hydraulic modelling at the system scale is the state-of-art approach in the nuclear energy sector. The possibility to couple such modelling tools to other domains through co-simulation paves the way to more diversified applications, particularly within the area of sustainable energies.

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