Dynamic Modelling of a Flat-Plate Solar Collector for Control Purposes

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Abstract

Two different dynamic models of a flat-plate solar collector have been developed in the Modelica language under Dymola® software.

These models have been developed within the Ambassador Project (Onillon, 2014). In this project, models of district heating components are conducted for control purposes, including a solar plant model.

The present article describes in detail each of these models along with the development process (e.g., assumptions taken into account). The model validation process and results are also presented, as well as the corresponding discussion and conclusions. The model's validation has been conducted by comparing the model's simulation results with the experimental results obtained in the IK4-TEKNIKER Solar Thermal Test Rig.

Keywords: Solar collector, Dynamic model, Control design, Modelica

1 Introduction

Solar water heating has received increased interest in recent years, primarily because it is a free energy source, and it is available, in principle, anywhere all over the world.

The key element in a solar heating plant is the solar collector field, as it is at the solar collectors that the solar energy is captured and transferred to the circulating fluid. Currently, the collector type most widely used in such plants is the flat-plate solar collector.

Heating demand coverage involves not only a certain quantity of heat energy but also a specific water temperature. Besides, in the case of solar plants, the energy source is non-manageable; therefore, it is even more difficult than in conventional plants to assure required supply conditions.

Because of that, well-developed control is essential in this type of facility to allow the fulfilment of supply requirements, which will depend on the application.

One of these applications is a solar water heating plant connected to a district heating system. This scenario is covered by the Ambassador Project. The core of this project is the development of suitable management by control algorithms, which assure optimum performance of the whole district energy system. Control design requires knowing in detail the physical behaviour of the system to be controlled; therefore, models of all the subsystems in the District Heating System, including the solar plant, are required.

Solar collectors are usually described by stationary models that consider the collector to be in steady-state operation (Hottel and Woertz, 1942; Hottel and Whillier, 1955; Bliss, 1959). Stationary models have the advantage of being simpler and hence needing less computation time than dynamic models. However, this simplification may be critical because solar collectors rarely reach a steady state during operation due to their large time constants and the variability of the driving forces. For several applications, e.g., the investigation of control strategies, it is desirable to take the collector dynamics into account (Schnieders, 1997; Ron, 1980).

Therefore, within this context, two flat-plate solar collector dynamic models have been developed in the Modelica language under the Dymola® environment: a Detailed Model and a Simplified Model.

2 The Detailed Model

Dynamic solar collector models can be classified into single capacitance (one node) models (Duffie and Beckman, 1991; Close, 1967), fluid flow direction distributed models (or 1xN node models) (Isakson, 1995; Muschaweck and Spirkl, 1993; Prapas, Norton et al 1988), and fluid flow direction and transverse distributed (or MxN node) models. Models of the last type try to represent the physical system in a more realistic way: apart from taking into account fluid temperature nodes (fluid flow direction), several temperature nodes at transverse directions are also used, with each one representing a solar collector component. There are several models developed in this way: 2x1 node (Klein, Duffie et al 1974), 2x node (Huang and Wang, 1994), 3x node (Ron, 1980), 4x node (Kamminga, 1985), or even more complicated ones (Oliva *et al*, 1991; Cadafalch, 2009).

In the present case, the so-called "Detailed Model", a 5x1 model, has been developed. On the one hand, transverse nodes represent the glass cover, the air inside the collector, the absorber, the fluid, and the rear insulation. Regarding the longitudinal discretization (fluid flow direction), at first a 5xn distributed model (8>n>1) was chosen, but it was determined that the discretization level increase in the fluid flow direction did not yield a relevant difference; therefore, it was discarded in favour of model simplicity.

In the model, the following heat flows are considered between the collector components:

- Convection between the glass cover and the air in the gap. For this case, a natural convection is considered as well as between this air and the absorber plate. The equations correspond to a free convection between a fluid and a plate, taking into account the possibility of the fluid being hotter than the solid and vice versa, and the tilt angle of the collector (Chapman, 1987)
- The fluid flow through the absorber plate is modelled via a forced heat convection imposed between the fluid lines and the absorber, taking into account both laminar and turbulent regimes (Verein Deutscher Ingenieure, 1997).
- Radiation heat transfer has been taken into account between the glass cover and the absorber plate.
- Conduction heat transfer between the absorber and the rear insulation is modelled (conduction in a Plane Wall) (Chapman, 1987).

In addition, heat transfer phenomena are also considered between the collector and the ambient, and has been modelled under the following conditions:

- Radiation between the glass cover and the sky. The model calculates the sky temperature from the value of the clearness index, the relative humidity and the ambient temperature.
- Both forced (wind action (Sartori, 2006)) and natural convections (same equations as for the collector internal convection) between the glass cover and the ambient are included. In the case of the rear insulation, only natural convection has been modelled.
- The solar radiation reaching the collector is applied to both the absorber and glass cover energy balances. For the glass cover, the element absorptivity is included as a parameter. With respect to that reaching the absorber, the glass cover transmissivity and the absorber absorptivity are taken into account, with both depending on the incidence angle of the solar radiation.

The scheme in Figure 1 represents the conceptual idea of modelled heat transfer phenomena.

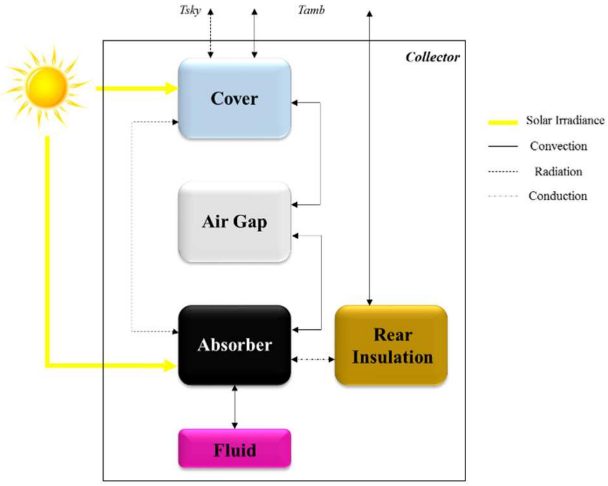

Figure 1. Schematic of heat transmission phenomena modelled in the Detailed Model

Following, physical assumptions associated with this type of model and those considered when developing the model are collected:

- All heat transport phenomena are taken to be in 1-D perpendicular to the flow direction, except for the heat carried by the flow. Perfect insulation is considered at the edges, so all heat transfer phenomena are related to the frontal collector area.
- With respect to the absorber, a harp type has been chosen; i.e., in each collector the fluid flow is distributed through a certain number of parallel tubes. The fluid flow is considered uniform along all the tubes in the absorber.
- Modelled pressure losses are those taking place at the collector harp tubes. Neither pressure losses at the input/output of the collector nor at the manifolds are modelled. This is because it was considered not important to develop specific detailed models for those elements. If real pressure losses need to be included, the best way to do it is by including data obtained from experimental tests (see Simplified Model in Section 3).
- Natural convection is considered between the rear insulation component and the ambient.
- As mentioned before, the solar energy not only affects the energy balance of the absorber plate (taking into account the glass cover's transmissivity and the absorber's absorptivity mentioned below) but also that of the glass cover itself.
- The cover's solar absorptivity is considered constant (independent of temperature and solar spectrum). However, the cover's transmissivity and IR absorptivity are dependent on incidence angle.
- Only fluid properties depend on temperature. The rest of the components' physical properties are not dependent on this variable. If desired, the components' properties, such as thermal inertias,

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can be easily turned into temperature-dependent properties by replacing the elements with those in the NewThermal Library (López, Hoyo, 2014).

A picture of the corresponding Modelica model built under the Dymola® environment can be observed in Figure 2.

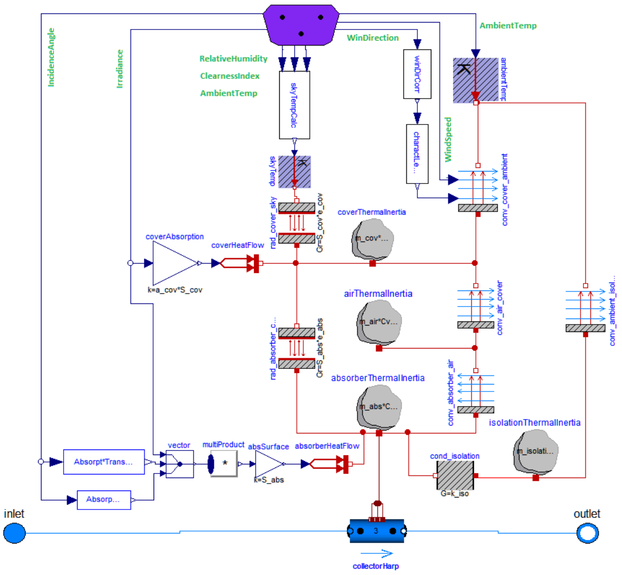

Figure 2. Solar Collector Detailed Model developed under Dymola® software

As shown in Figure 2, the Detailed Model is built with models from the Modelica Standard Library, mainly, `HeatCapacitor`, `ThermalConductor`, `Convection`, `BodyRadiation`, and `DynamicPipe`.

Each of the primary components in the solar collector (glass cover, air inside the gap, absorber plate, and rear insulation) is modelled as a thermal inertia with a certain uniform temperature finite volume (`HeatCapacitor`).

The fluid model itself represents an incompressible fluid and it is characterized by the value of its main properties, such as density, viscosity, specific heat capacity, conductivity and vapour pressure. Any fluid model included in the Modelica Standard Library can be used (`DynamicPipe` selector), but for the validation phase (see Section 4), a specific fluid model (Tyfocor LS) has been developed.

To simulate the behaviour of the collector when exposed to the solar radiation with a fluid circulating inside via the Detailed Model, apart from the model parameters, the following inputs are needed:

- Irradiance in the plane of the collector
- Incidence angle of solar radiation
- Clearness index
- Relative humidity
- Ambient temperature
- Wind velocity and direction
- Fluid input port conditions (i.e., mass flow rate and temperature)

It can be observed that the model's discretization level is high, so it can be easily adapted to other solar collector designs. To achieve this, it includes many parameters (e.g., geometries and various material physical properties), inputs and state variables.

3 The Simplified Model

As mentioned, the described Detailed Model has a significant number of parameters, and many of them are related to geometrical and thermal properties of the materials, which are not usually provided by the manufacturer. Therefore, it could be difficult to set up the Detailed Model.

The purpose of the Simplified Model is to develop a workable model; i.e., one that provides the most representative solar collector dynamics using the minimum number of parameters that are easy to obtain, with a minimum simulation time.

Regarding the model's parameters, several standards have been developed to normalize the solar collector's performance data via solar thermal collector testing. Historically the US ASHRAE standard (93-77) was the first one to be widely used. Next, the ISO 9806 series of standards was developed and from them, the EN 12975. Several national standards are also available outside of Europe, most often based on the ISO 9806, but in Europe the EN 12975 has replaced all national standards.

Taking as a reference EN12975, it distinguishes between steady state test conditions and quasi-dynamic test conditions. Currently the most common tests between manufacturers are those performed under steady state conditions.

$$\begin{aligned}\dot{Q}/A = F'(\tau\alpha)_{en}G^* - c_1(t_m - t_a)\\ - c_2(t_m - t_a)^2\end{aligned} \tag{1}$$

Equation (1) represents the static behaviour of a flat-plate solar collector according to EN12975. The standard describes tests for working out all of the parameters in the equation: those related to the heat reaching the fluid (F'), and those related to collector thermal losses (c_1, c_2). Currently there are a couple of Modelica libraries including solar collector models based on equation (1)[1].

However, within the standard stationary tests' descriptions, additional optional test procedures are included, which is the case for the effective thermal capacity (c_5) and the incidence angle modifier ($K_{\theta b}(\theta)$). Including these two additional parameters results in the

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[1] AixLib library (SolarThermal model), and Building Systems library (ThermalCollectorDynamic model)

following equation representing the collector, also included in the referenced standard:

$$\dot{Q}/A = F'(\tau\alpha)_{en}K_{\theta b}(\theta)G^* - c_1(t_m - t_a) - c_2(t_m - t_a)^2 - c_5\frac{dt_m}{dt} \qquad (2)$$

Related to the effective thermal capacity, it involves an equivalent collector global thermal capacity, lumping into one temperature node the heat capacities of all the collectors' components. By simply adding this parameter to equation (1), it becomes dynamic, resulting in a solar collector model type called a Single-capacitance (or one node) model.

In this way, the dynamic behaviour is considered, not in a detailed way but adequately for use of the model for control design purposes.

Therefore, equation (2) is chosen as the model basis for the Simplified Model. Currently there is a Modelica library already including a dynamic solar collector model that takes into account this thermal capacity; however its approach is different from that shown at equation (2)[2].

It must be noted that in equation (2), mean fluid temperature *(t_m)* is considered the arithmetic mean between the inlet and outlet temperatures of the collector. This finding implies theorizing a linear temperature distribution in the collector, as several authors did previously (Close, 1967). However, according to other authors (Duffie and Beckman, 1991), in reality, this distribution is not observed. In the EN 12975 standardized test the arithmetic mean is used; therefore, because this standard is the reference for the Simplified Model, the arithmetic mean will also be used in this case.

Equation (2) actually represents a thermal energy balance, where the following terms appear:

- The useful energy gain, as heat energy absorbed by the fluid ($\dot{Q}$), In the equation it appears as energy per unit collector area (A).
- Solar radiation absorbed by the collector, which depends on the collector's efficiency factor (F'), the effective transmittance-absorbance product for normal incidence ($\tau\alpha_{en}$), the incidence angle modifier for beam radiation ($K_{\theta b}(\theta)$), and the global hemispheric solar radiation (G).
- Energy losses, calculated according to parameters obtained from the standardized tests (c_1, c_2), ambient temperature (t_a), and fluid arithmetic mean temperature (t_m).
- Energy storage, calculated from effective thermal capacity (c_5), and fluid arithmetic mean temperature variation.

Related to hydraulic behaviour, fluid pressure losses are also included in the model. The measurement of the collector pressure loss, although optional, is included in the referenced standard tests. Therefore, an ad-hoc model has been developed (`pressureLoss`) and included in the model to apply the corresponding total pressure losses according to the data obtained from the tests. This component initially applies the least squares method to approximate the test data to a 2nd order polynomial function without an independent term, for later calculation of the pressure drop depending on the flow rate during the simulation.

A picture of the corresponding Modelica model built under Dymola® environment can be observed in Figure 3.

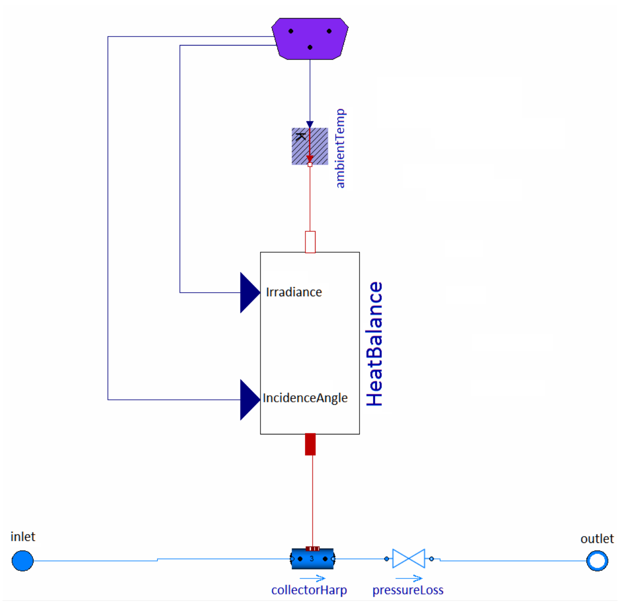

Figure 3. Solar Collector Simplified Model

In the previous figure, `HeatBalance` model is used to compute the heat flow calculation according to equation (2) and transmit it to the fluid (collectorHarp `DynamicPipe`). Despite 3 nodes being defined at the collectorHarp, the calculated heat flow is only applied to the central one. The extreme nodes are only used to calculate the mean fluid temperature.

In the case of the Simplified Model for the simulation, when exposed to the solar radiation with a fluid circulating inside, just the following inputs are needed:

- Irradiance in the plane of the collector
- Incidence angle of solar radiation
- Ambient temperature
- Fluid input port conditions (i.e., mass flow rate and temperature)

3.1 Series and Parallel configuration

In both centralized and decentralized solar plants, solar collectors are usually connected together in series,

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[2] Buildings library (ASHRAE93 model and EN12975 model)

parallel or a combination of series and parallel arrangements.

To simulate the whole solar field would require the development of the corresponding simulation models based on the connections of the individual solar collector models, which would be very tiresome. Because of that, based on the described Simplified Model, two additional models have been worked out for the simulation of series and parallel arrangements of collector modules, respectively.

In a parallel-connected collector array, the flow of the heat transfer fluid is divided and a proportion goes through each collector in the array. This mainly involves the same pressure drop and the same temperature increment, and thus the same collector efficiency. Facing modelization coming from the Simplified Model, the parallel connection of N solar collectors is equivalent to a unique solar collector with an area N times larger, an N times higher heat capacity, an N times higher number of tubes, and the same pressure drop. In this new model (`ParallelArray` model), apart from the simplified collector model parameters, the user only needs to set up the number of solar collectors in the collector array.

Conversely, in a series-connected collector array, all of the heat transfer fluid passes through all of the collectors. This transfer primarily involves a pressure drop and output temperature increase; thus, collector efficiency decreases in the fluid flow direction. In this case the developed model is equivalent to a unique solar collector with the same number of tubes but N times longer, discretized into N+2 nodes in the flow line (`SeriesArray` model). The net heat flow calculated at each solar collector (balance of heat gain, heat losses, and heat storage) is applied to each one of the N central nodes. In the `SeriesArray` model, apart from the Simplified Model parameters, the user has to set up the number of solar collectors in the collector array, and the percent of additional pressure drop with respect to the theoretical array pressure drop (N times the individual solar collector pressure drop) due to the additional pipe length for the connections.

To check the developed models, simulations have been carried out in Dymola®, and simulation results have been compared between these new models and the corresponding assembly of individual simplified collector models. The checking has been carried out for the N=3 case, under certain ambient and fluid conditions (see Case B conditions at Section 4). The comparison of the obtained collector array outlet temperatures for the parallel and series connection is shown at Figure 4 and Figure 5, respectively.

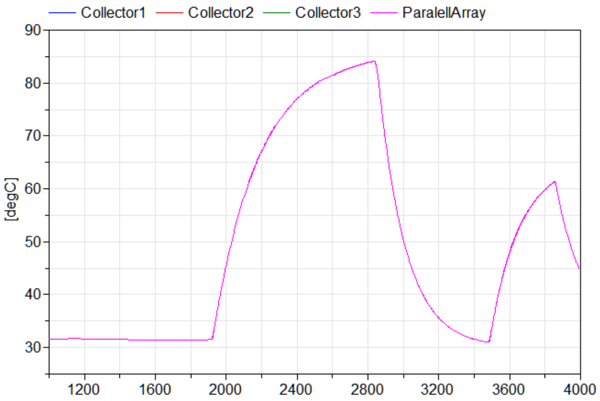

Figure 4. Outlet temperature comparison for the parallel arrangement configuration.

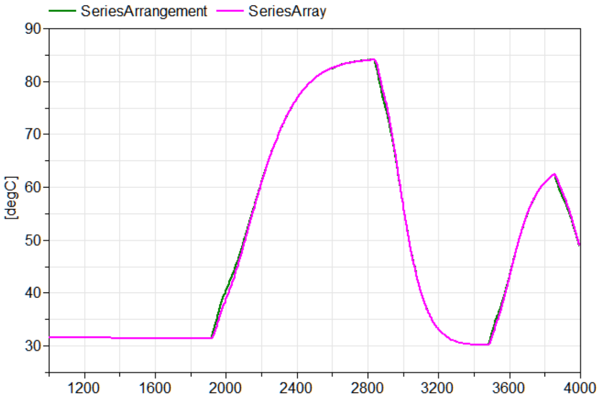

Figure 5. Outlet temperature comparison for the series arrangement configuration.

As expected, in the parallel configuration all outlet temperatures coincide perfectly: between individual collectors, and also with the `ParallelArray` model.

In the case of the series arrangement, the length of each flow control volume (node) of the `SeriesArray` model (N+2 = 5 nodes) is different from that of the series connection of 3 individual collectors (3N = 9 nodes). This involves small differences between the outlet temperatures, as indicated in Figure 5, which are more obvious in the transient states (error <1%). It is considered that based on the small error obtained, the developed model behaviour is good, and it is not worth increasing the number of control volumes in the `SeriesArray` model.

4 Validation of the Detailed and Simplified Models

Two flat-plate solar collectors' dynamic models have been developed: the Detailed Model, and the Simplified Model. The validation of these models is carried out by comparing experimental data with the models' simulation results of a specific flat-plate solar collector working under certain operating conditions.

Experimental data are obtained from the Solar Thermal Test Rig located at IK4-TEKNIKER facilities (LER), normally used for the characterization of solar thermal components, such as flat-plate solar collectors. This facility has a fully sensorized and actuated solar thermal installation, including a mini-weather station to collect meteorological data. In this facility, the fluid comes out of a DHW tank and is driven by the primary pump to the collector. Before reaching that point, the fluid passes through some heaters that increase the fluid temperature up to the desired value. The fluid makes its way to the collector where it is heated by solar radiation, and finally it goes back to the DHW tank, thus closing the circuit.

For validation, an appropriate environment has been developed in Dymola® for the Detailed Model and the Simplified Model simulations, to simulate their behaviour when working under ambient conditions with a fluid passing through. Among other things, this included the implementation of ad-hoc calculation models needed to turn available experimental data into the required input data for the Simplified and Detailed models.

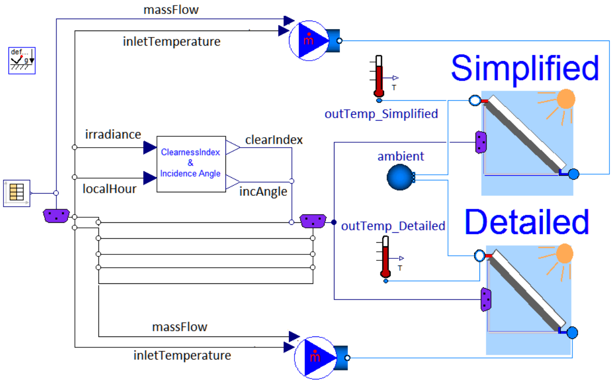

Figure 6. Dymola® environment for the Simplified Model and the Detailed Model simulations.

Regarding the models' parameters values, in the case of the Simplified Model they were obtained from the corresponding collector performance test report carried out according to UNE-EN 12975-2:2006 by a testing laboratory accredited by ENAC. In the case of the Detailed Model, most of the parameters' values were collected from the collector manufacturer's technical data sheets, and the rest (e.g., physical properties of certain materials) from specialized literature (Duffie and Beckman, 1991; Chapman, 1987).

In this type of plant, the heat transfer fluid degrades over time, so its properties values also change. In this case, when experimental tests for validation were carried out in the LER, the fluid was not fresh; therefore, in pursuit of representativeness/veracity in the simulation results, real physical properties were used for the fluid model definition instead of those coming from the technical data sheets. For that purpose, a fluid sample was removed from the circuit and characterized just after performance of the tests. Thus, reliable values for quantities such us density, thermal conductivity, specific heat capacity and dynamic viscosity depending on temperature value were available for the simulations.

The aim of the validation process is to check the capability of the developed models to represent collector behaviour in general, and dynamic performance specifically. For that purpose, the following three collector operation cases have been established:

- Case A: mass flow rate variation (increasing steps), for almost constant incident solar radiation and inlet temperature values.

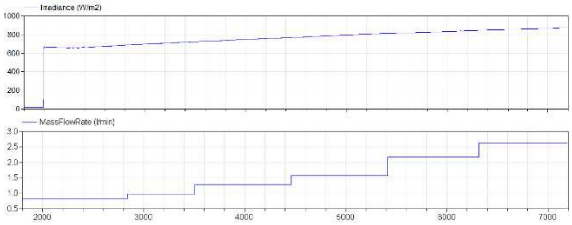

Figure 7. Case A mass flow rate profile.

- Case B: incident solar radiation with sudden variation (covered/uncovered), for different mass flow rates, with an almost constant inlet temperature

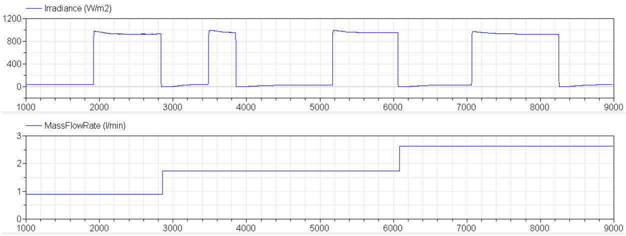

Figure 8. Case B irradiance and mass flow rate profiles.

- Case C: increasing inlet temperature, with decreasing incident solar radiation (not controlled) and almost constant mass flow rate

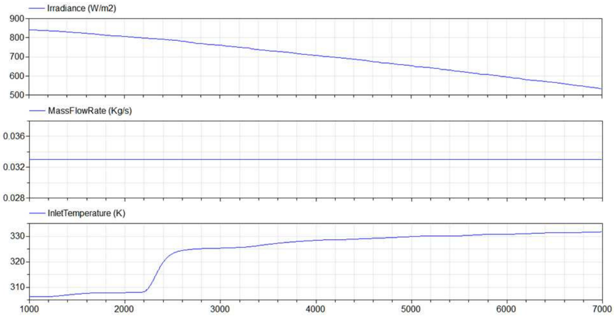

Figure 9. Case C Irradiance, mass flow rate, and inlet temperature profiles.

These cases allow the analysis of the models' responses to the variation of the possible controlled variables in this type of plant (mass flow rate and inlet temperature), and the main non-manageable perturbation (solar irradiance).

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The resulting collector's outlet temperature value over the time at each case is shown in the following figures.

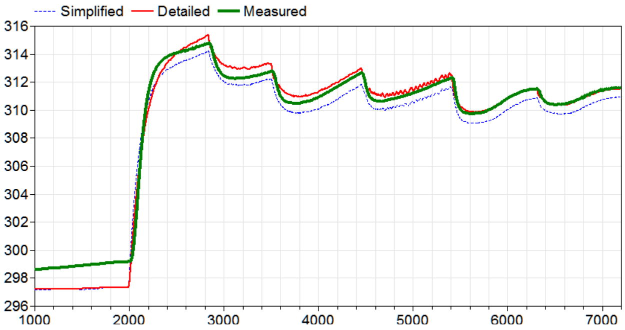

Figure 10. Case A outlet temperatures.

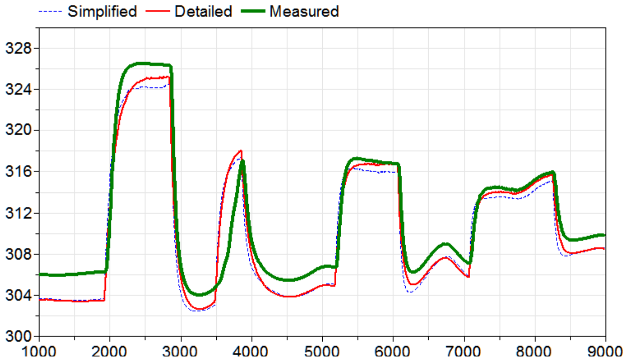

Figure 11. Case B outlet temperatures.

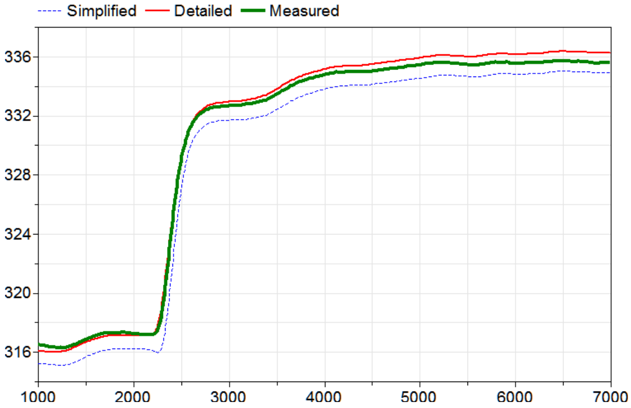

Figure 12. Case C outlet temperatures.

5 Discussion

For validation, as shown in Figure 10, Figure 11, and Figure 12, the collector outlet temperature values are very similar. An initial offset can be observed between the experimental data and the simulation models' results, especially for case A and B. This finding is observed because at the LER, when the experiment starts, the solar collector is covered, which avoids radiation entrance but also prevents direct convection phenomena to the ambient, while in the simulation models, this convection does occur (more losses, lower outlet temperature). Obviously, this offset, or a consequence of it, remains during the rest of the simulation.

Conversely, it must be noted that the outlet temperature slope with changing input values (mass flow rate, incident solar radiation, or inlet temperature) is very much alike in the three cases, which means that in both models the physical dynamics are properly modelled.

From these findings, it is concluded that both of the developed models are appropriate for representing the dynamic (and also the static) behaviour of a flat-plate solar collector. However, it is worth highlighting that depending on the application, one can be more suitable than the other.

Table 1. Models characteristics comparison.

	Detailed	*Simplified*
N. parameters	29	14
N inputs	9	5
N. continuous time states	7	3
CPU time[3]	15.1	

As shown in Table 1, the Detailed Model has a larger number of parameters, whose values can be difficult to ascertain. It also has a greater number of time states involving a greater CPU time. However, due to the high degree of detail, this model is more suitable than the Simplified Model for analysing the influence of particular system variables, such as individual components' geometry or material, on collector performance. This capability is very valuable, for example, for modelling design improvements.

As for the Simplified Model, again paying attention to the results appearing in Table 1, it is ultimately more user-friendly. Simulation time is lower and therefore more suitable for control design purposes because it is normally necessary to perform numerous simulations to, for example, identify the controlled system. The only requirement is to have access to collector parameters obtained from the referenced standard test.

For cases in which direct access to standard test parameters is not possible, the Detailed Model may be the only way to obtain them. In this situation, the corresponding standard test load cases can be simulated using the Detailed Model instead of doing it experimentally, thereby obtaining the necessary Simplified Model parameters' values. This may also be a more affordable way.

Finally, when a controller is developed, a common final step in this process is the fine controller parameter tuning, which is normally carried out by driving the real system. However, simulations of the designed controller using the Detailed Model can be worked out instead, thus allowing for cost saving, and avoiding damage to the real system.

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[3] Relation between Detailed/Simplified Models CPU times for Case A simulation.

6 Conclusions

Two flat-plate solar collector models have been developed in the Modelica language: the Detailed Model and the Simplified Model. It has been demonstrated that both provide a suitable representation of solar collector dynamic behaviour. However, there are differences between them that make them suitable for different applications.

The Detailed Model uses a high quantity of elements, parameters, and inputs, allowing for a complete and detailed analysis of the solar collector. This characteristic is suitable mainly for collector design purposes, such as studying components' material/geometry influence, etc.

The Simplified Model is a more workable model, with fewer but more accessible parameters based on standard tests. This type of model is primarily appropriate for control design purposes. In fact, within Ambassador Project, developed Simplified Model has been used to identify the flat-plate solar collector system via model simulations, getting to a transfer function (outlet temperature depending on inlet mass flow rate) consisting on a first-order system and a pure delay.

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