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SolarReceiver2D: a Modelica Package for Dynamic Thermal Modelling of Central Receiver Systems

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Abstract: This paper describes the Modelica Package SolarReceiver2D which has been developed for the dynamic thermal analysis of central receiver systems. The package includes all the components necessary for the dynamic simulation of the solar receiver operation and it enables consideration of different receiver geometries, materials, HTFs, and operating conditions (e.g., HTF mass flow rate control strategies, heat flux, ambient conditions). Some of the package components are taken from existing Modelica libraries originally developed to model water and gas flows, while other are implemented as new components. The SolarReceiver2D package allows assessment of the receiver thermal efficiency and the temperature distributions experienced by the tubes and the HTF during its operation. The tubes temperature field is modelled in the axial, circumferential, and radial directions, and this makes the package suited for a thermo-mechanical analysis of the receiver. Moreover, the receiver response to passing clouds is dynamically simulated accounting for the effect of thermal transients. The SolarReceiver2D represents a useful tool for the design and optimization of solar tower receivers.

Keywords: Modelica, Solar Receiver, Concentrating Solar Power, Dynamic simulation, Solar Energy.

1. INTRODUCTION

Solar Tower plants represent a promising technology to produce dispatchable and flexible electric power exploiting the solar resource Gentile and Manzolini (2022). One of the main components of a Solar Tower plant is the receiver, whose design and operation are crucial to reduce costs and increase efficiency of this promising renewable technology. The complex heat transfer phenomena that characterize the receiver operation, require to have advanced modelling tools able to estimate the receiver thermal efficiency and the temperature distributions experienced by the Heat Transfer Fluid (HTF) and the receiver tubes during its operation. Rodríguez-Sánchez et al. (2014, 2018) developed various steady thermal models to evaluate the temperature distributions of HTF and receiver walls using both one-dimensional (1D) and two-dimensioanal (2D) modelling approaches. In the 1D case each receiver tube is discretized along the axial direction and constant heat flux and temperature are assumed along the circumferential one whereas in the 2D case tubes are discretized in both directions. The aforementioned thermal models do not enable dynamic analysis of solar receiver operation nor have they been implemented adopting acausal modelling, as it will be done in this work. In this context, Montañés et al. (2018) applied the acausal modelling technique to simulate the behaviour of a Parabolic Trough plant and Li et al. (2016) for the dynamic analysis of an open air receiver of Solar Tower plants. Recently, Picotti et al. (2020, 2022) adopted the acausal approach to implement two dynamic thermal models of an external receiver using Modelica. They highlighted a remarkable potential of the acausal modelling approach in simulating heat transfer phenomena taking place in solar receivers. A comprehensive review of dyanamic models of solar tower receivers is provided in Marti et al. (2020).

In this paper, the Modelica Package SolarReceiver2D for the dynamic thermal analysis of central receiver systems is described. The package allows dynamic simulation of solar receiver operation, considering different HTFs or materials for the receiver tubes. While a 1D modelling approach was adopted in Picotti et al. (2020) the SolarReceiver2D package enables 2D thermal analysis of solar receivers. The package is based on the model described in Picotti et al. (2022) but improvements have been made to enhance the model accuracy (e.g. crossed strings method is used for the view factors assessment and a local correlation is adopted to assess the natural convection heat transfer coefficient instead of a global one). The paper is organised as follows: Section 2 provides an overview of the Modelica package and reports the methodology and the assumptions adopted

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for the receiver modelling, in Section 3 the different components of the SolarReceiver2D package and the main equations that characterize their mathematical modelling are described, Section 4 demonstrates the application of the Modelica Package to a simple case study, and Section 5 draws the main conclusions of the study and anticipates possible future developments.

2. PACKAGE OVERVIEW

The SolarReceiver2D package is encoded using the equation-based, object-oriented language Modelica. This language is an open standard built on acausal modeling, allowing for simulation of large, complex, and heterogeneous systems (The Modelica Association (2021)). A significant number of publications highlighted the potential of an object-oriented modelling paradigm to model power plants or components such as heat exchangers and turbomachinery (Casella and Schiavo (2002); Casella and Leva (2003, 2006); Picotti et al. (2020, 2022)). In the case of solar receiver modelling the Modelica language brings several advantages: i) physical systems are described through equations that define their behaviour rather than a sequence of operations to compute outputs from given inputs; equations can be either explicit or implicit and modality and the order in which they are written does not matter; ii) the non linear algebraic and differential equations can be written as they are on paper and the solver deals with their symbolic manipulation and eventually solve them; therefore, no resolution algorithm has to be implemented by the end-user and this remarkably simplifies the model development, documentation, modification and reuse; iii) models are organized in a hierarchical structure, in which more complex models are obtained by connecting basic models; iv) several libraries have been developed and are freely-available to model components such as heat exchangers; the models of these libraries can be easily adapted to the specific case study and this strongly facilitates the receiver model implementation.

2.1 Central Receiver System

The SolarReceiver2D package is designed to model external receivers for Solar Tower plants (or central receivers systems). Within these plants the sun rays are reflected by a large number of heliostats towards the top of a centrally-located tower where the receiver is installed. The latter is typically made of two independent flow paths (namely eastern and western flow path) composed by different panels in series, each of them made of several parallel tubes. The panels of the flow paths create two serpentines covering the two halves of the receiver lateral surface. The cold HTF enters the receiver from the most irradiated side, it is divided in the two flow paths, and flows within the tubes of each panel until reaching the outlet on the other side of the receiver; here the two flows are collected and typically sent to the hot tank of the Thermal Energy Storage system. The mass flow rate flowing in the two paths is set by two different controllers which aim to have an outlet temperature as close as possible to the nominal value.

2.2 Modelling approach

A schematic overview of the receiver thermal model implemented through the SolarReceiver2D package is provided by Fig. 1 where the main components of the package and their interaction are depicted. The thick blue lines represent fluid connectors which exchange information on the fluid thermodynamic state and its mass flow rate, the orange thick lines represent 2D spatially distributed heat connectors, and the thin black lines represent generic data connectors.

On the left side of Fig. 1 it can be noticed how the two flow paths are fed by the two components "Source Mass Flow" which set the mass flow rate of each flow path according to the information provided by a Proportional-Integral (PI) controller. The latter receives as input the HTF temperature measured by the component "Temperature Sensor" at the outlet of the flow path and controls the mass flow rate for the subsequent time step in order to have an outlet temperature approaching as much as possible its nominal value. In each side of the receiver the HTF flow within the tubes is modelled in the "Flow path" component. Lastly, the HTF coming from the two sides of the receiver is collected in the component "Sink".

A detail of the component "Flow Path" is given in the right side of Fig. 1: the HTF flow is modelled in the component "Fluid Flow" where the fluid energy balance is solved. The thermal power absorbed by the HTF is evaluated accounting for the power reflected by the solar field (obtained starting from the heat flux maps within the component "Heat Source") and for three thermal loss contributions: radiative and convective losses at the front side of the tubes, and convective losses only at the back side of the tubes. The latter is considered directly attached to an insulation layer. The heat conduction within the tubes walls and through the insulation layer is modelled in the components "Metal Tube 2D" and "Insulation Layer (Back)", respectively.

Each receiver tube is discretized in the radial, axial, and circumferential direction. More precisely, in the radial direction only three nodes are considered, respectively at the internal, medium, and external radius. In order to reduce the computational cost only one tube per each panel is modelled, and the heat flux hitting the panel-representative tube in each axial volume is obtained as the average of the heat fluxes hitting all the panel tubes in the corresponding axial position; moreover, headers and manifolds are not modelled since they are computationally expensive, though with a negligible thermal contribution. In addition, due to the assumed symmetric flux distribution on each tube in the circumferential direction, only one half of the tube is modelled.

A schematic representation of the half-tubes discretization along the circumferential direction is provided in Fig.2, where it can be observed how the thermal power ($Q_{SF,i,j}$) reflected by the solar field towards each i,j-th element of the half-tube (the index i moves in the axial direction and the index j in the circumferential one) is partially reflected ($(1-\alpha)Q_{SF,i,j}$), partially lost due to radiative losses ($Q_{rad,i,j}$), partially lost due to convective losses in the front and back sides of the tubes ($Q_{conv,i,j}$), and partially absorbed by each i,j-th element of the tube wall. The latter term is then divided into two amounts transferred

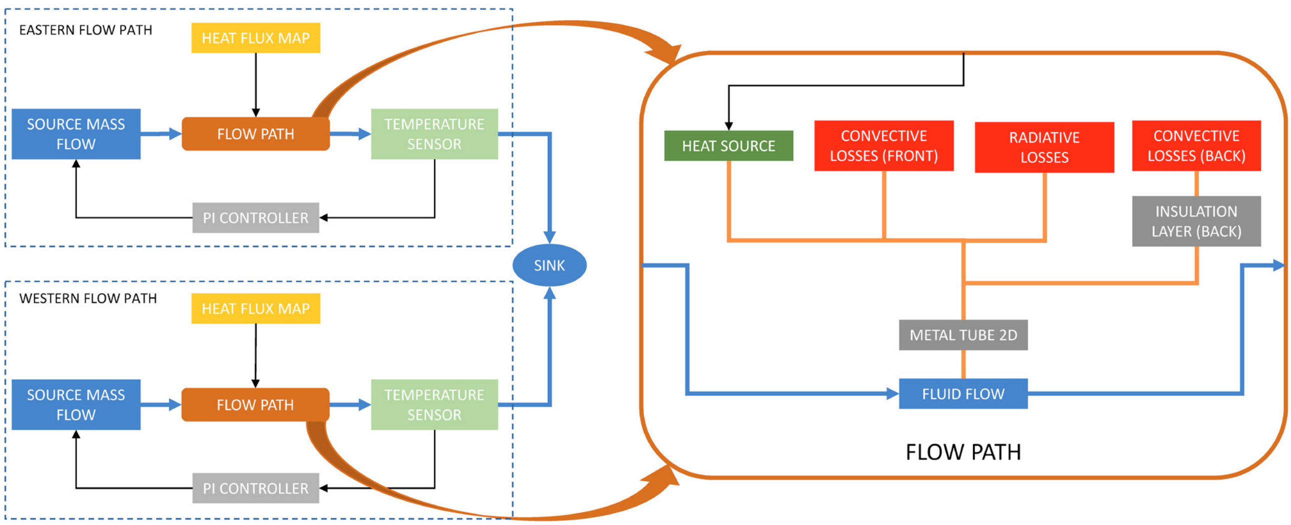

Fig. 1. Schematic overview of the receiver model implemented through the SolarReceiver2D Modelica package; thick blue lines represent fluid connectors, orange thick lines represent 2D spatially distributed heat connectors, and thin black lines represent generic data connectors.

to the next and previous elements in the circumferential directions and the remaining amount absorbed by the HTF.

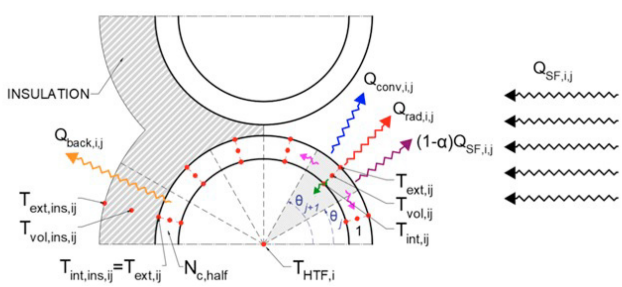

Fig. 2. Detail of the half tube cross section highlighting the thermal power flows and the radial and circumferential discretization

3. PACKAGE COMPONENTS DESCRIPTION

The different components of the Modelica Package "SolarReceiver2D" are described in this section. Some of them are part of the Modelica Standard library (`https://github.com/modelica/ModelicaStandardLibrary`), some other are taken from the ThermoPower library (`https://casella.github.io/ThermoPower/`), originally implemented by Casella and Leva (2003, 2006) to model water and gas flows, and the remaining ones are developed as new components in the SolarReceiver2D package. In detail:

- the component "Heat Flux Map" corresponds to the Modelica standard library component "`Modelica.Blocks.Sources.CombiTimeTable`", and it is used to provide the temporal distribution of the heat flux hitting each axial volume of the panel-representative tubes;
- the component "PI Controller" is obtained coupling the components "`Modelica.Blocks.Continuous.LimPID`" and "`Modelica.Blocks.Math.Add`" both available in the Modelica standard library;
- the components "Source Mass Flow", "Temperature Sensor", and "Sink" are obtained starting from the components "`ThermoPower.Water.SourceMassFlow`", "`ThermoPower.Water.SensT1`", and "`ThermoPower.Water.SinkPressure`", respectively. All of them are available in the ThermoPower library and are adopted replacing the medium package (originally water) with the HTF one; depending on the HTF of the receiver that must be simulated (e.g. Solar Salts or Sodium), the different medium packages available in the SolarTherm modelica library (`https://github.com/SolarTherm`) can be adopted.
- the components "Fluid Flow","Heat Source", "Convective Losses (Front)", "Radiative Losses", "Convective Losses (Back)", "Metal Tube 2D", and "Insulation Layer (Back)" are developed as new Modelica components as described in Subsections 3.1-3.7, respectively.

  In all of these components, two-dimensional heat terminals are used to impose that at the interface between two components connected through heat connectors (orange thick lines in Fig. 1): i) the temperature on the two sides of each i,j-th element is the same; ii) the sum of the thermal power entering the two sides of the terminal in each i,j-th element is equal to zero.

  The two-dimensional heat terminals are developed as new Modelica components in the SolarReceiver2D package ("`SolarReceiver2D.Interfaces.DHTVolumes2D`"), and they are implemented adapting the one-dimensional terminals available in the ThermoPower library ("`ThermoPower.Thermal.DHTVolumes`").

3.1 *Fluid flow*

The component "Fluid Flow" is developed as a new Modelica component in the SolarReceiver2D package ("`SolarReceiver2D.Components.Flow1D2DFV`"). The compo-

nent allows a mono-dimensional simulation of the HTF flow within the half tube representing each flow path and it is obtained by inheritance from the ThermoPower component "`ThermoPower.Water.Flow1DFV`". The two-dimensional heat terminal "`DHTVolumes2D`" is introduced for the connection with the "Metal Tube 2D" component. Such terminal allows to model the heat transfer from each circumferential volume of the half tube to the corresponding fluid volume. More precisely, the thermal power absorbed/released by the HTF in each axial volume is equal to the sum of the power crossing the internal wall in each tube circumferential volume, doubled in order to account for the half tube not explicitly modelled.
The component "`ThermoPower.Water.Flow1DFV`" allows to use several internal heat transfer models, each characterized by a different Nusselt number correlation for the evaluation of the fluid heat transfer coefficient. In the SolarReceiver2D package, the Petukhov correlation replaced by the Dittus-Boelter one for Reynolds numbers higher than 10000 is introduced and used in the "Fluid Flow" component (Picotti et al. (2020)). The detail of the fluid mass, momentum, and energy balance equations are given in (Casella and Leva (2003)).

3.2 Heat Source

The component "Heat Source" is developed as a new Modelica component ("`SolarReceiver2D.Components.HeatSource`") and includes a "Real Input" connector for the connection with the component "Heat flux map" and a two-dimensional heat terminal ("`DHTVolumes2D`") for the connection with the component "Metal Tube 2D".
Within the Heat Source component the thermal power absorbed by each portion of the half tube is assessed by means of Eq. (1) where $q''_{SF,i}$ is the heat flux hitting the i-th element of the panel (provided by the component "Heat flux map"), r_{ext} is the tubes external radius, L_i is the length of each control volume in the axial direction, α is the tubes coating absorptivity, and $\overline{\theta_j}$ is the mean angle of each circumferential element.

$$\dot{Q}_{\mathrm{in},ij} = \begin{cases} q''_{SF,i} \cdot r_{ext} \cdot L_i \cdot \left(\sin\left(\theta_{j+1}\right) - \sin\left(\theta_i\right)\right) \cdot \alpha \\ \qquad\qquad\qquad\qquad \text{if} \quad \overline{\theta_j} \leq \pi/2 \\ 0 \qquad\qquad\qquad\quad\;\; \text{if} \quad \overline{\theta_j} > \pi/2 \end{cases} \tag{1}$$

3.3 Convective losses (front)

The component "Convective Losses (Front)" ("`SolarReceiver2D.Components.ConvectiveLossesFront`") includes a single two-dimensional heat terminal ("`DHTVolumes2D`") for the connection with the component "Metal Tube 2D". In this component the convective losses in the front side of the tubes are assessed accounting for forced and natural convection through Eq. (2):

$$Q_{conv,i,j} = h_{\mathrm{mix},i,j} A_{ext,i,j} \left(T_{ext,i,j} - T_{amb}\right) \tag{2}$$

where $A_{ext,i,j}$, $T_{\mathrm{ext},i,j}$, and $h_{\mathrm{mix},i,j}$ are the external area, the external wall temperature, and the overall heat transfer coefficient (air side) of each i,j-th element of the tube. The latter is evaluated through Eq. (3) as function of the coefficients for the natural ($h_{\mathrm{nc},i,j}$) and forced convection ($h_{\mathrm{fc},i,j}$) (Incropera and DeWitt (1996)).

$$h_{\mathrm{mix},i,j} = \left(h^{3.2}_{\mathrm{nc},i,j} + h^{3.2}_{\mathrm{fc},i,j}\right)^{\frac{1}{3.2}} \tag{3}$$

The forced convection is modelled through the global correlations for a cylinder in cross-flow proposed by Siebers and Kraabel (1984). The authors reported several correlations for different values of the cylinder surface roughness. In the case of external receivers, the surface roughness can be estimated as the ratio between the tubes radius and the receiver diameter. All the air thermodynamic properties are evaluated at the receiver film temperature, which is obtained as the arithmetic mean between the ambient temperature and the average between the external wall temperatures ($T_{\mathrm{ext},i,j}$) of all of the tubes element in the front side ($\overline{\theta_j} \leq \pi/2$).
The natural convection heat transfer coefficient is calculated through the global correlation for a vertical flat plate proposed by Siebers and Kraabel (1984). More precisely, a heat transfer coefficient for each receiver panel is evaluated as function of the average temperature of the panel external side.

3.4 Radiative losses

The component "Radiative Losses", similarly to "Convective Losses (Front)", is developed as a new component ("`SolarReceiver2D.Components.RadiativeLosses`") and includes the two-dimensional heat terminal "`DHTVolumes2D`" for the connection with the component "Metal Tube 2D". The thermal power lost due to radiative heat exchange in each i,j-th element of the tubes is computed through Eq. (4) where σ_{SB} is the Stefan-Boltzmann constant, T_{eq} is the equivalent surrounding temperature (Eq. (5)), ε_t and ε_{ins} are the tube and insulation layer emissivities, $F_{ext,j}$ is the view factor between each tube element and the external environment, and $F_{ins,j}$ is the view factor of each tube element towards the portion of insulation layer between two adjacent tubes. The temperature of this portion is assumed equal to the temperature of the tube external wall in the circumferential element $j = N_c/4+1$ and in the corresponding axial position. All the view factors are two-dimensional and are obtained through the crossed strings method.

$$\begin{aligned} \dot{Q}_{rad,i,j} &= \frac{\sigma_{SB}\left(T^4_{ext,i,j} - T^4_{eq}\right)}{\frac{1-\varepsilon_t}{\varepsilon_t A_{\mathrm{ext},i,j}} + \frac{1}{F_{\mathrm{ext},j} A_{\mathrm{ext},i,j}}} + \\ &+ \frac{\sigma_{SB}\left(T^4_{\mathrm{ext},i,j} - T^4_{ext,i,\frac{Nc}{4}+1}\right)}{\frac{1-}{\varepsilon_t A_{\mathrm{ext},i,j}} + \frac{1}{F_{\mathrm{ins},\;,j} A_{\mathrm{ext},i,j}} + \frac{1-\varepsilon_{ins}}{\varepsilon_{ins} A_{ins},i}} \end{aligned} \tag{4}$$

$$T_{eq} = \left(\frac{\varepsilon_{sky} T^4_{sky} + \varepsilon_{gr} T^4_{gr}}{\varepsilon_{sky} + \varepsilon_{gr}}\right)^{0.25} \tag{5}$$

3.5 Convective losses (back)

The component "Convective losses (back)" ("`SolarReceiver2D.Components.ConvectiveLossesBack`") allows the assessment of the convective losses in the back side of the tubes. The latter are calculated through Eq. (6) and they depend on the natural convection heat transfer coefficient ($h_{nc,back}$), the external area of each i,j-th element of the insulation layer ($A_{ext,ins,i,j}$), and the external temperature of each i,j-th element of the insulation layer ($T_{ext,ins,i,j}$).

$$Q_{conv,i,j} = h_{nc,back} A_{ext,ins,i,j} \left(T_{ext,ins,i,j} - T_{amb}\right) \tag{6}$$

A single heat transfer coefficient is considered for the back side of the tubes, and its value is obtained through the global correlation for a vertical flat plant suggested by Siebers and Kraabel (1984) as function of the average temperature of the insulation layer external wall.

3.6 Metal Tube 2D

The component "Metal Tube 2D" ("`SolarReceiver2D.Components.MetalTube2D`") includes two two-dimensional heat terminals: the internal one is connected to the component "Fluid flow" while the external one is used for the connection with the components "Heat source", "Convective losses (front)", "Radiative losses", and "Insulation layer (back)". By connecting different components to the same heat terminal the power balance is automatically formulated so that the power crossing the external wall of each *i,j*-th element of the half-tube is calculated as the power absorbed by the tubes (component Heat Source) minus the three thermal losses (components "Convective losses (front)", "Radiative losses", and "Convective losses (back)"). Within "Metal Tube 2D" the energy balance equation for each *i,j*-th element of the tube wall is written as:

$$m_{i,j} c_m \frac{\partial T_{vol,i,j}}{\partial t} = \dot{Q}_{ext,i,j} + \dot{Q}_{int,i,j} + \dot{Q}_{n,i,j} + \dot{Q}_{p,i,j} \quad (7)$$

where: c_m is the specific heat capacity of the tubes material; $m_{i,j}$ and $T_{vol,i,j}$ are the mass and the volume temperature of the *i,j*-th element of the tube wall; $\dot{Q}_{ext,i,j}$ is the power crossing the external wall of each tube element that depends on the power reflected by the solar field toward the receiver and on the three loss terms; $\dot{Q}_{int,i,j}$ is exchanged at the internal thermal port and depends on the HTF temperature and heat transfer coefficient; $\dot{Q}_{n,i,j}$ and $\dot{Q}_{p,i,j}$ represent the amounts of thermal power exchanged with the next and the previous volumes of the tubes wall in the circumferential direction.

3.7 Insulation layer (back)

The component "Insulation Layer (Back)" ("`SolarReceiver2D.Components.InsulationLayer`") is obtained starting from the component "`ThermoPower.Thermal.MetalTubeFV`" and replacing one of the two one-dimensional heat terminal with the two-dimensional "`DHTVolumes2D`". The component is used to model the heat conduction in the radial direction through the insulation layer attached to back sides of the tubes. In detail, adopting the same approach used for "Metal Tube 2D", Eq. (8) is applied in each *i,j*-th element of the insulation layer, where $\dot{Q}_{ext,ins,i,j}$ and $\dot{Q}_{int,ins,i,j}$ represent the thermal power crossing the external and internal wall in the *i,j*-th element of the insulation layer.

$$m_{ins,i} c_{ins} \frac{\partial T_{vol,ins,i,j}}{\partial t} = \dot{Q}_{ext,ins,i,j} + \dot{Q}_{int,ins,i,j} \quad (8)$$

4. CASE STUDY AND RESULTS

To demonstrate the SolarReceiver2D package applicability, a simple case study is considered: a Solar Salts (60% $NaNO_3$, 40% KNO_3) receiver similar to the one adopted in the Crescent Dunes ST plant (SolarReserve (2014)), characterized by a nominal power output of 100 MWel and a nominal receiver thermal input of around 700 MWth.

The main receiver characteristics are reported in Table 1. The receiver tubes are assumed to be made of Inconel Alloy 740H, whose mechanical and physical properties are taken from (Special Metals (2021)). The insulation layer (fiberglass) properties are taken from (Electronics Cooling (2008)). The plant operation is simulated during two typical clear-sky and cloudy days considering the sun path of March 21st. The Direct Normal Irradiance (DNI) daily profiles are taken from measured data in Eldorado Valley (NV, USA) with a 10 minutes temporal resolution. The heat flux maps on the two receiver flow paths in each analyzed time step are obtained through the tool SolarPilot (Wagner and Wendelin (2018)) adopting the heliostats aiming strategy "Image Size Priority".

Table 1. Main receiver characteristics

Item	Symbol	Value
Receiver height (m)	H_{rec}	30.5
Receiver diameter (m)	D_{rec}	15.8
Number of panels	N_p	14
Number of tubes per panel	N_t	64
Tubes external diameter (mm)	d_{ext}	52.9
Tubes inernal diameter (mm)	d_{int}	49.6
Distance between tubes (mm)	s_t	2
Insulation layer thickness (mm)	s_{ins}	200
HTF inlet temperature (°C)	T_{in}	290
HTF nominal outlet temperature (°C)	$T_{out,nom}$	565

Figures 3 and 4 report the trends of the outlet temperature and mass flow rate of the HTF flowing in each receiver flow path during the two investigated days. In Fig. 3 it can be noticed how the HTF outlet temperatures are close to the nominal value for most of the hours during the clear sky day. The mass flow rate of the two flow paths follow analogous but different trends: the western side of the receiver is supplied with a higher mass flow rate during the morning than during the afternoon; the opposite goes for the eastern side. Fig. 4 points out that the fluctuations in solar irradiance cause a reduced outlet temperature is some hours of the day. This happens because the mass flow rate reaches the minimum value allowed by the controller, hence the decrease in solar irradiance cannot be compensated by a further reduction in HTF flow rate.

5. DISCUSSION AND CONCLUSIONS

The paper describes in detail the components of the Modelica Package SolarReceiver2D for the dynamic thermal analysis of solar tower receivers. To demonstrate its applicability, the SolarReceiver2D package is exploited for the analysis of a simple case study and the main results are reported in this paper. They highlight the capabilities of the package in simulating the operation of a solar tower receiver during clear sky days as well as cloudy days, for which the clouds passages lead to significant and rapid variations of the receiver thermal input. The SolarReceiver2D package represents a useful tool for the receiver design phase since it enables comparison of different geometries, materials and HTFs. Moreover, since the temperature field in the tubes is modelled in the axial, circumferential, and radial directions, the package is suited

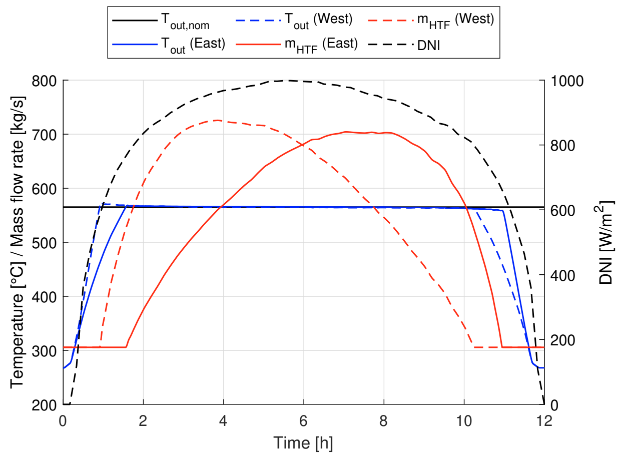

Fig. 3. Trends of DNI, HTF outlet temperature, and mass flow rate for the investigated clear sky day

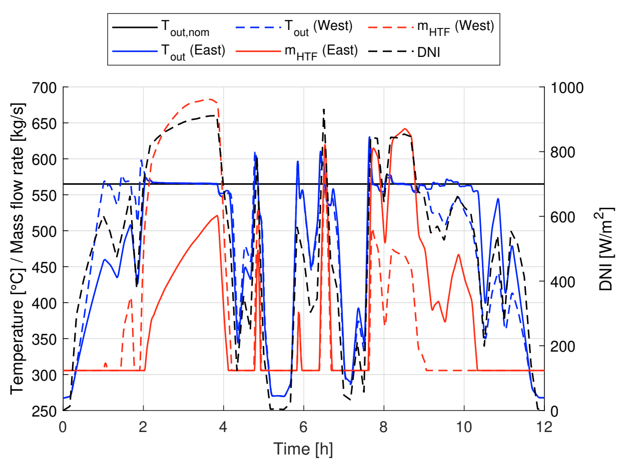

Fig. 4. Trends of DNI, HTF outlet temperature, and mass flow rate for the investigated cloudy day

for a thermo-mechanical analysis of the receiver. The latter can be performed evaluating pressure stresses due to HTF internal pressure and thermal stresses originated by wall temperature gradients in the three directions; then, history data of temperature and stresses can be used to assess the creep-fatigue lifetime of each receiver panel. Moreover, the package can be adopted to optimize the receiver operation, comparing different HTF mass flow rate control strategies as well as different heliostats aiming strategy.

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