Simulation of the Start-Up Procedure of a Parabolic Trough Collector Field with Direct Solar Steam Generation

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Abstract

Solar thermal power plants are one of the most interesting options for renewable electricity production. For a plant based on parabolic trough collectors, the start-up procedure of the solar field in the morning has to be well defined in order to start electricity production as soon as possible. In this paper, the Modelica language is used to describe the thermo-hydraulic components of the collector field. A control system for the plant start-up is developed based on the Modelica *StateGraph* library. With this simulation model a number of studies are performed to estimate the time consumption of the start-up procedure.

Keywords: parabolic trough; solar; control

1 Introduction

Among the wide range of renewable energy technologies for electricity production, solar thermal power plants are one of the economically most interesting options. Direct solar irradiation is concentrated into a focal point or focal line by curved mirrors. Parabolic trough collectors use the high temperatures to heat up a fluid in absorber tubes arranged in the focal line. The use of an organic oil as a heat transfer fluid is state of the art. Benefits are expected by directly evaporating and superheating water in the absorber tubes (direct solar steam generation, DISS) [1]. For the implementation of a first plant, the aspect of start-up and shut-down has to be solved. While the power block itself might operate through the night by using a thermal energy storage or an auxiliary fossil boiler, the solar field cools down at night.

As long as the solar field has not reached its operating point in terms of pressure and temperature, the steam turbine can not be started. Table 1 illustrates the impact of the start-up procedure duration on the levelized costs of electricity. If the procedure can be shortened by 1 hour a net gain of 7.9 % will be obtained.

This paper presents simulation studies covering the topic of solar field start-up procedures for parabolic trough fields with direct steam generation. Especially the two-phase flow conditions inside the absorber tubes necessitate the analysis with the help of detailed numerical simulations. Having a simulation tool at hand, different start-up strategies can be tested and evaluated to come to an optimal solution. The Modelica language is used for the study since combination of hydraulic, solar and control components can easily be achieved. Some central aspects of the model and the results of the numerical simulation will be presented in the following.

Table 1: Impact of plant start-up time on the costs of electricity generation.

Start-up time	0 min	30 min	60 min
Relative costs	100.0 %	103.5 %	107.9 %

2 General structure of the model

To cover the central aspects of the simulation task, the model is split into two parts,

- the plant layer and
- the control layer.

In the plant layer all hardware components like pipes, absorber tubes, tanks and junctions are represented. The control layer incorporates all elements of the control system, i.e. controllers, parameter definitions, set-point tables and the process sequence control. The control layer is defined as

```
model StartUp_Controller_Var1
    …
end StartUp_Controller_Var1;
```

An instance of this model named `Control` is created in the plant layer.

```
model plant_layer_design_01
  StartUp_Controller_Var1 Control;
end plant_layer_design_01;
```

The exchange of data between the two layers is enabled by a data bus which is defined as a connector element.

```
connector Bus
 Real Signal_Real[n_Signals_Real];
 parameter String[:] Names_Real =
     fill("n.a.",n_Signals_Real);
 parameter Integer n Signals Real =
     size(Names_Real,1);
end Bus;
```

The array `Signal_Real` hosts the data, while the parameter `Names_Real` allows the specification of names for the single data channels. An instance of the connector class is defined as an inner variable in the plant layer and as an outer variable in the control layer. In Dymola, the size of the array and the descriptions can easily be defined via the graphical user interface. For connecting real signals to the bus, a port is defined as:

```
model BusPort_Real_In

 outer DissDyn.Signal.Bus Bus;
 Modelica.Blocks.Interfaces.
    RealInput u;
  parameter Integer SignalNumber
   (min=1, max=Bus.n_Signals_Real);
equation
  u=Bus.Signal_Real[SignalNumber];
end BusPort_Real_In;
```

The parameter `SignalNumber` identifies the bus channel that should be connected to the signal plugged to input u. To graphically distinguish between ports, that assign a signal to a bus variable and ports that readout a bus variable, two port definitions `Real_In` ▸1➡ and `Real_Out` ◁1⬅ are used. In parallel to the real bus variables, Integer and Boolean variables are included in the bus in the same manner. The graphical annotation of the signal number is helpful for the setting-up and checking of the model.

3 Plant layer

The central element of the plant layer is the hydraulic circuit composed of buffer tank, feedwater header, absorber tubes and live steam header. Figure 1 illustrates the arrangement of the components for the reference configuration of a 5 MW_{el} solar field [3]. From the seven parallel rows of the plant layout, only one is modeled in the simulation together with mass flow multipliers at the inlets and outlets. Between the evaporation and superheating section a phase separator is arranged to allow recirculation operation. The water separated from the steam is transported by means of a drainage line to the buffer tank from where it is pumped back to the inlet of the field. During normal operation, the connection from live steam header outlet to the buffer

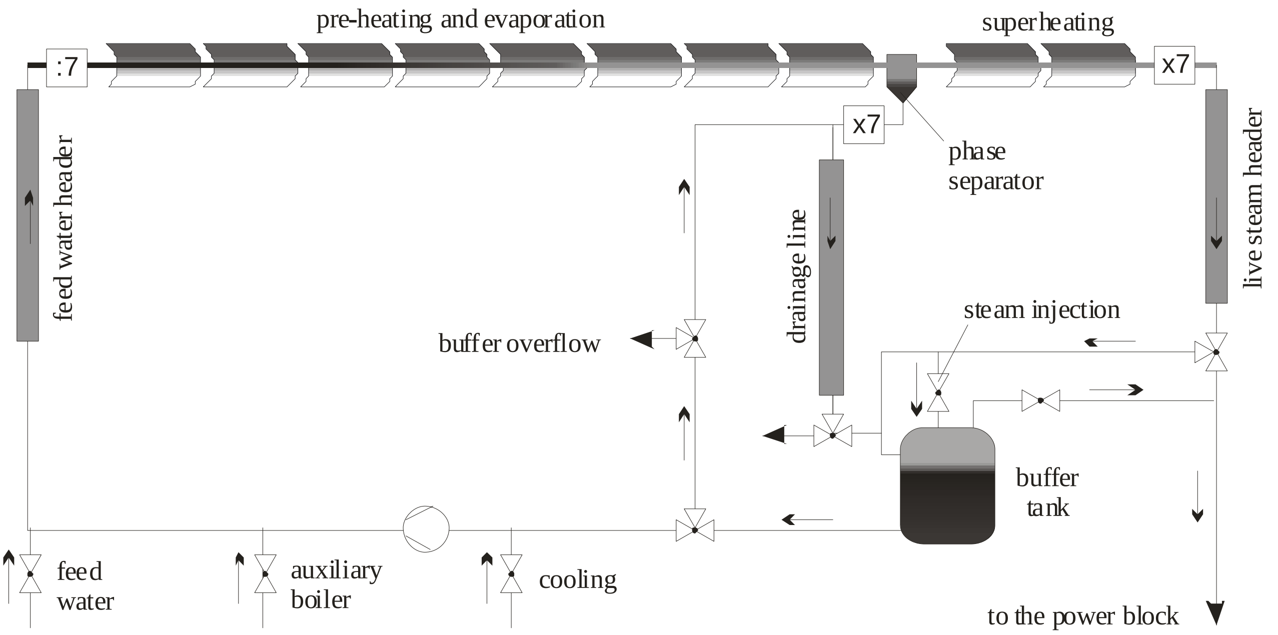

Figure 1: diagram of the plant layer

tank is closed so that the superheated steam directly flows to the power block. During the start-up phase this connecting line is opened and the drainage line closed. This allows recirculation of water over the whole system (global recirculation). The recirculated water is mixed with fresh feed water and, if necessary, with hot water produced by an auxiliary boiler. Another input line for cold water is added to cool the recirculation pump and thus to avoid cavitation in this device. The buffer tank is designed to hold water and steam at saturation conditions. There is one drain for the water at the bottom and one for steam at the top of the tank. Table 2 gives the geometrical parameters for the components used in this study.

The components models are taken from the *DissDyn* library developed at DLR [2]. For all pipe components, a one-dimensional discretization is used with the state variables pressure, specific enthalpy and wall temperature in each control volume. As boundary conditions, mass flow and specific enthalpy have to be provided at the inlet and pressure at the outlet. For the plant configuration, this means that a time dependent pressure boundary condition is required at the outlet of the live steam header. In the first part of the start-up procedure the flow from the field is sent to the power block. In the later stage of global recirculation, the directional control valve is switched to lead the flow into the buffer tank. For the first case, a constant pressure can be used as a boundary condition. For the second case, the boundary condition is directly coupled to the pressure in the buffer tank. A special component is designed to switch the boundary condition from a constant value to the pressure in the tank by means of a ramp. For the recirculation pump it is assumed that the power always fits to the pressure lift over the pump.

From the buffer tank steam can be extracted to the power block. If the buffer pressure falls below a given limit, steam from the field outlet can be injected for stabilization. To keep the buffer liquid level within the allowed limits, water can be taken off into the buffer overflow line which leads to the power block or to the inlet of the drainage line.

Table 2: Geometrical parameters of the plant components, length l, inner tube diameter d_i, outer tube diameter d_a, number of elements for spatial discretization n.

	l [m]	d_i [mm]	d_a [mm]	n [-]
feedwater header	210	60	70	12
evaporator	812	55	70	61
superheater	200	55	70	17
live steam header	210	100	120	12
drainage line	350	100	110	10
buffer tank	10.2	1000	1050	1

All valves shown in the plant diagram are implemented as mass flow definitions. This approach avoids the high effort of using valve characteristics and the corresponding controllers.

4 Control layer

The start-up procedure is treated as a directed sequence of processes which themselves consist of a sequence of sub-processes. To model this structure, the Modelica *StateGraph* library is applied where each state element represents the corresponding process or sub-process. A state can either be active or inactive. A state element and its successor in the chain are linked by a transition. In case the state is active and its successor is inactive, the transition is enabled. This means, that the transition will fire as soon as a Boolean condition becomes true. After this event, the successor is active and the state has fallen back to inactive. Providing the first state with the active attribute this attribute will be passed through the whole sequence of states, and indicates which process in the system is running at each moment. The transitions between the states are linked to Boolean criteria described by system variables and switching conditions. A possible transition might be that a certain temperature or pressure is reached in the system. Figure 2 shows a screenshot of the control layer with the 9 main processes passed through during the simulation from top to bottom. Some of the main processes are divided into sub-processes by means of a parallel element. At this element, the path, and with it the active attribute, diverges into two branches where one of them exists of just a single state and the other is composed of a sequence of states. The transition that follows the parallel element, becomes enabled not before the final states in each branch both become active. This structure is chosen, since some of the processes require a number of minor steps that have to be passed before the process itself is finished. For analysis of the simulation results it is useful to define a subprocess identifier that represents the actual system state in terms of a numerical value

$$S = \sum_{i} state[i].active \times weight[i] \quad ,$$

with the *weight* being an array with monotonically increasing values.

While the described structure helps to define the actual state and its chronological sequence, the input signals for the plant are generated in a number of control systems. The following elements are used to react on a change in the system state:

- On/Off switch that is triggered by two input signals “switch to on” and “switch to off”
- Switch that chooses between two real inputs depending on the status of the Boolean input signal
- Set-point table that selects the output value from a set of Boolean expressions and their dedicated real values
- Real expressions incorporating Boolean expressions that checks if one of the assigned states is active.

These components are completed by control elements that do not react on the system state itself but on characteristic variables of the systems:

- Hysteresis and min/max elements that check if real input signals extend given limits
- Proportional-integral controllers
- Algebraic expressions depending on a number of input variables

Without going into detail on the individual control loops table 3 summarizes the main control activities and the type of control applied for this task.

5 Simulation results

The developed start-up strategy will be described together with the simulation results. Nevertheless, some aspects like the boundary conditions should be treated beforehand.

5.1 Boundary conditions

It is assumed that from the shut-down procedure of the last evening warm water is stored in the feed water tank (6 bar, 154°C, 20 m^3) and in the buffer tank (60 bar, 275°C, 6.4 m^3). This water can be used to pre-heat the solar field. An auxiliary boiler is available that generates water or steam at different pressure levels. In the morning, the temperature in the field has fallen to 30°C. The whole volume in the field, except the buffer tank, is full of water.

5.2 Simulation of the start-up procedure

Figure 3 shows the results of the start-up simulation. At time t=0 the collectors are focused. Up to this point, the field is pre-heated. The collectors are fo

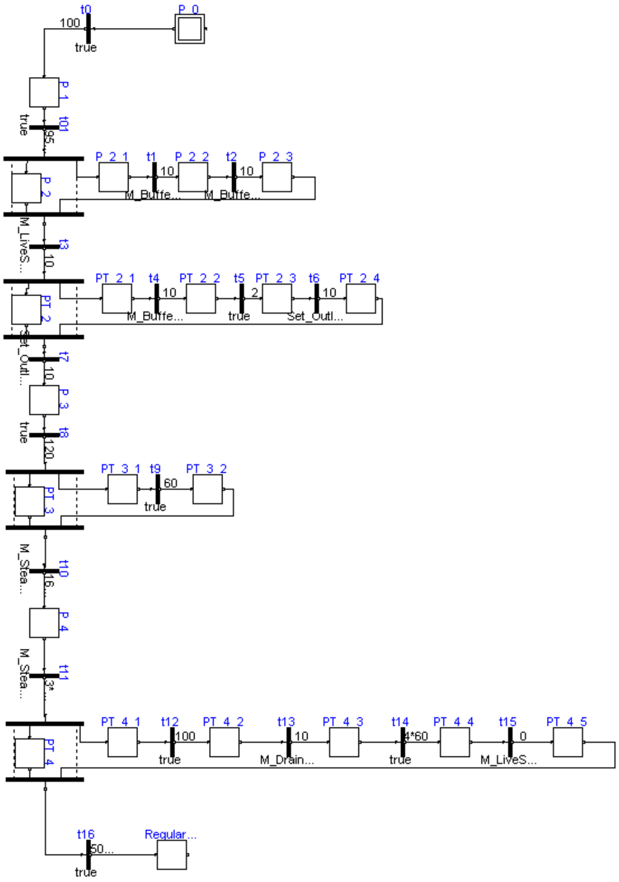

Figure 2: Screenshot of the control layer composed of `state`, `transition` and `parallel` elements from the StateGraph library.

Table 3: Main control tasks and types of control element used for them

feed water mass flow	PI-controller algebraic expression on/off switch set-point table
feed water temperature	algebraic expression set-point table
recirculation mass flow	set-point table
buffer pressure	PI-controller
buffer overflow	hysteresis element
recirculation cooling	algebraic expression
auxiliary power	algebraic expression
collector focusing	on/off switch
separator drainage	on/off switch

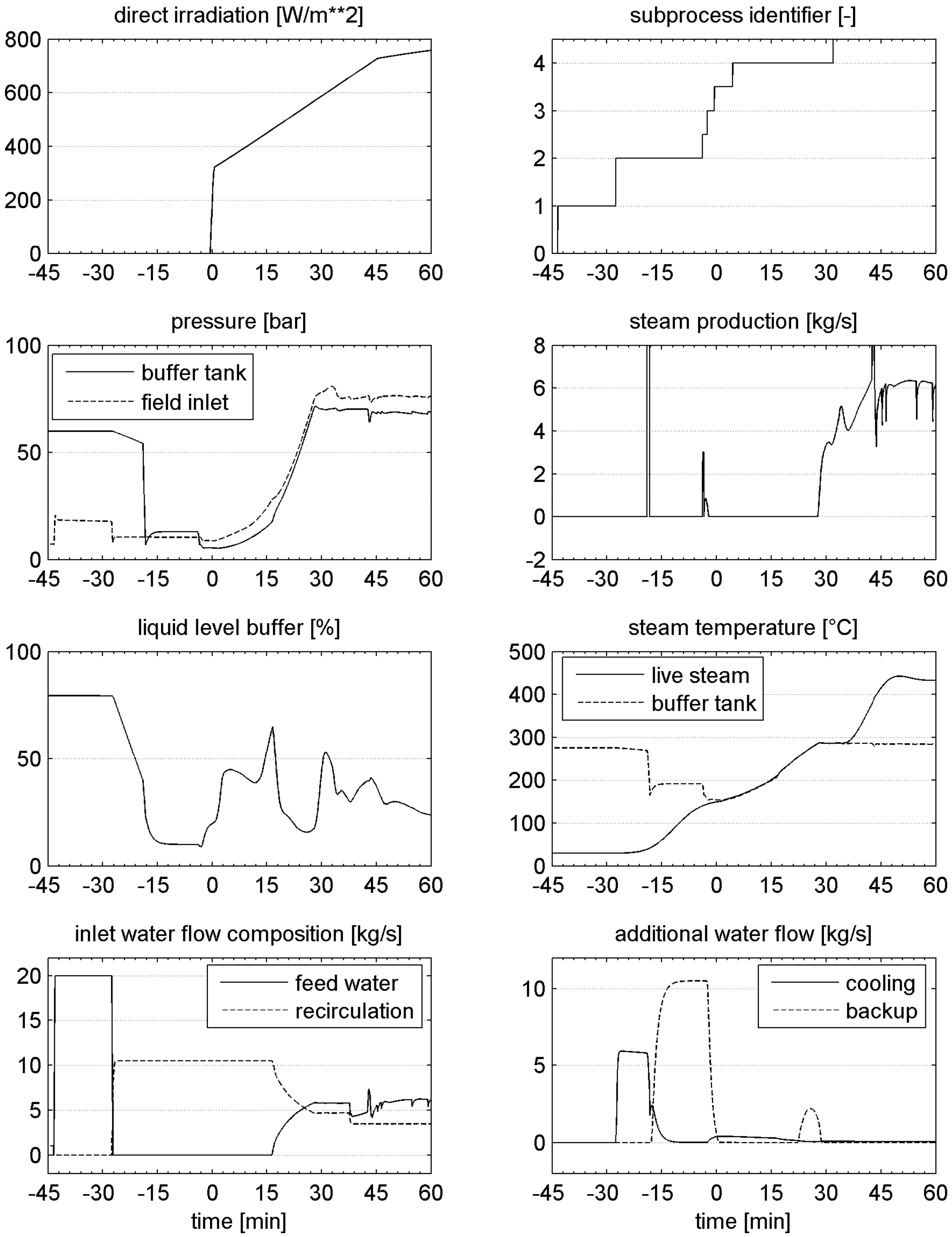

Figure 3: Start-up procedure in terms of important system variables.

cused at a solar altitude of 10° (at time t=0 min). Up to an altitude of 20° (at time t=45 min) shading between collectors occurs. The direct solar irradiation signal is corrected by these two effects that reduce the effective solar input on the collectors. The impact of the shading is illustrated in figure 4.

Pre-heating the field with warm water from the feed water tank

As a first step, warm water from the feed water tank is send into the field (t=-42 min). Form the temperature signal it can be seen that the pre-heating does not reach the end of the field when the feed water tank is completely emptied (at t=-27 min). The pressure is remained on a low level since evaporation in the field should start as early as possible. The water pushed out from the field is directed to the power block.

Pre-heating the field with hot water from the buffer tank

The water from the buffer tank is mixed with additional cold water to bring the temperature below the saturation temperature in the field. This is necessary to avoid evaporation in the feed water header which would otherwise prevent a controlled distribution of the water on the parallel channels. The flow into the field is fixed at 10.5 kg/s from which about 4.5 kg/s originate from the buffer tank. At t=-17 min the buffer tank falls below its minimum level but the temperature at the field outlet is still low. Redirecting the flow from the field outlet into the buffer tank would lead to a pressure decrease in the tank. For this reason, the pre-heating of the field is continued with water from the auxiliary boiler (named backup boiler in the figure) until the field outlet temperature reaches 150°C. This condition becomes true at t=-3 min.

Global recirculation without solar input

The connection between field outlet and buffer tank is opened and recirculation over the buffer tank is started. The pressure signals from buffer tank and field inlet are now linked. Since water of 150°C is mixed with the water of 165°C in the buffer tank, a slight temperature drop and, in the consequence, pressure drop in the buffer occurs.

Global recirculation with solar input

After 3 min of waiting time, the collectors are focused and solar heat input into the system starts. No steam is extracted from the system so the pressure in the field continuously rises. When the first steam is produced in the absorber tubes, large amounts of water are displaced and send to the buffer tank. Since outflow of the tank is nearly constant, the liquid level rises and finally triggers additional water extraction from the tank. The maximum water temperature at the field inlet is set to a value of 200°C that corresponds to the nominal operating conditions. From a tank pressure of 16 bar on, the recirculated water exceeds this temperature limit. For maintaining the desired temperature, cold feed water is mixed with the hot water from the buffer tank. The mass flow of recirculated water is reduced to maintain a constant total flow. This effect can be clearly seen from the feed water and recirculation water signals in figure 4.

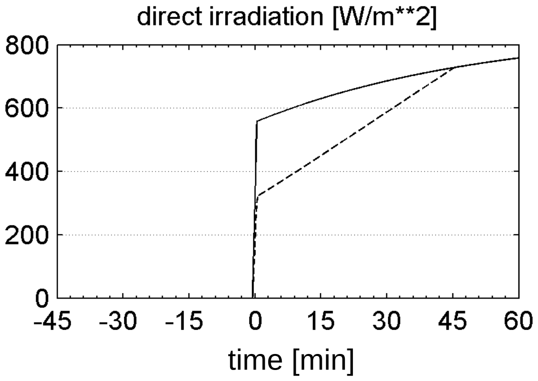

Figure 4: Impact of shading (- -) between two parallel collector rows on the effective direct irradiation compared to a stand-alone collector (---).

Steam extraction to the power block

Having reached the nominal operation pressure of 70 bar, saturated steam is extracted from the buffer tank to keep the pressure constant. The automatic feed water control is activated although its output does not yet reach the value provided by the automatic cooling of the inlet water.

Switching from global to local recirculation

As soon as the drainage line is pre-heated to a temperature of 250°C and the steam extraction from the buffer tank reaches 3.5 kg/s, the separator drainage is opened and water from the drainage line is send to the buffer tank. The inlet of the superheating section falls dry and the field outlet temperature rises. At a steam temperature of 350°C, the connection from the field outlet to the buffer tank is closed and the steam is directly sent to the power block. For the operation of the drainage system, it is now important to maintain the pressure in the buffer tank constant. Parallel to the steam extraction valve, a steam injection is included to prevent the pressure from falling below the limit.

End of the start-up procedure

When the steam temperature reaches 400°C the start-up procedure is considered as completed and plant control can switch to nominal operation mode. This point is reached 44 min after focusing the collectors.

5.3 Solar-only start-up

If hot water for pre-heating the field is not available in the morning, the field has to be started in solar-only mode. Figure 5 shows the simulation results. In addition, no auxiliary boiler is used in this configuration. The start-up time from focusing the collectors is 55 min that means 11 min longer than with pre-heating. On the first glance, this seams to be not much. From the pressure increase it can be seen that the initial time lag at 7 bar pressure is 20 min which reduces to a value of 13 min during the following process. Since the process in solar only mode takes place later, the solar input is already on a higher level and more heat is provided into the system. Having reached the 70 bar, it takes 45 s in the solar-only mode until the steam production meets 3.5 kg/s and the switching to local recirculation is started. In contrast to that in the pre-heating version, the same procedure takes 252 s, since heat input into the system is significantly less.

5.4 Start-up at low irradiation

A reduced level of solar irradiation can e.g. be caused by haze in the atmosphere. To estimate the impact on the start-up procedure simulations are performed with a modified parameter in the solar irradiation model that represents a turbid instead of a clear sky atmosphere. From figure 6 it can be seen that the start-up time is increased by 12 min. The procedure itself stays similar to the original configuration.

6 Conclusions

The developed Modelica simulation model has proven its capability to simulate complex fluid-dynamic processes like the ones taking place during the start-up of a parabolic trough solar power plant. The interdisciplinary approach of the Modelica language is used to combine the thermo-hydraulic components with a control system. Simulation runs show that a start-up time of about 55 min is necessary to reach nominal operation conditions. The long duration is mainly attributed to the low solar input after sunrise which results from the shading between two parallel collector rows. The start-up can be accelerated by 13 min when pre-heating the field with water stored in the feed water tank and in the buffer tank from the last evenings shut-down. The developed control concept is stable even if a reduce level of solar irradiation is assumed. Based on the cost estimate given in the introduction, the reduction by 13 min would lead to 2% lower electricity costs. Although this number is not high further potential is expected by improving the start-up strategy.

Acknowledgements

The authors would like to thank the German Ministry for the Environment, Nature Conservation and Nuclear Safety for the financial support given to the SOLDI project under contract No. 16UM0024.

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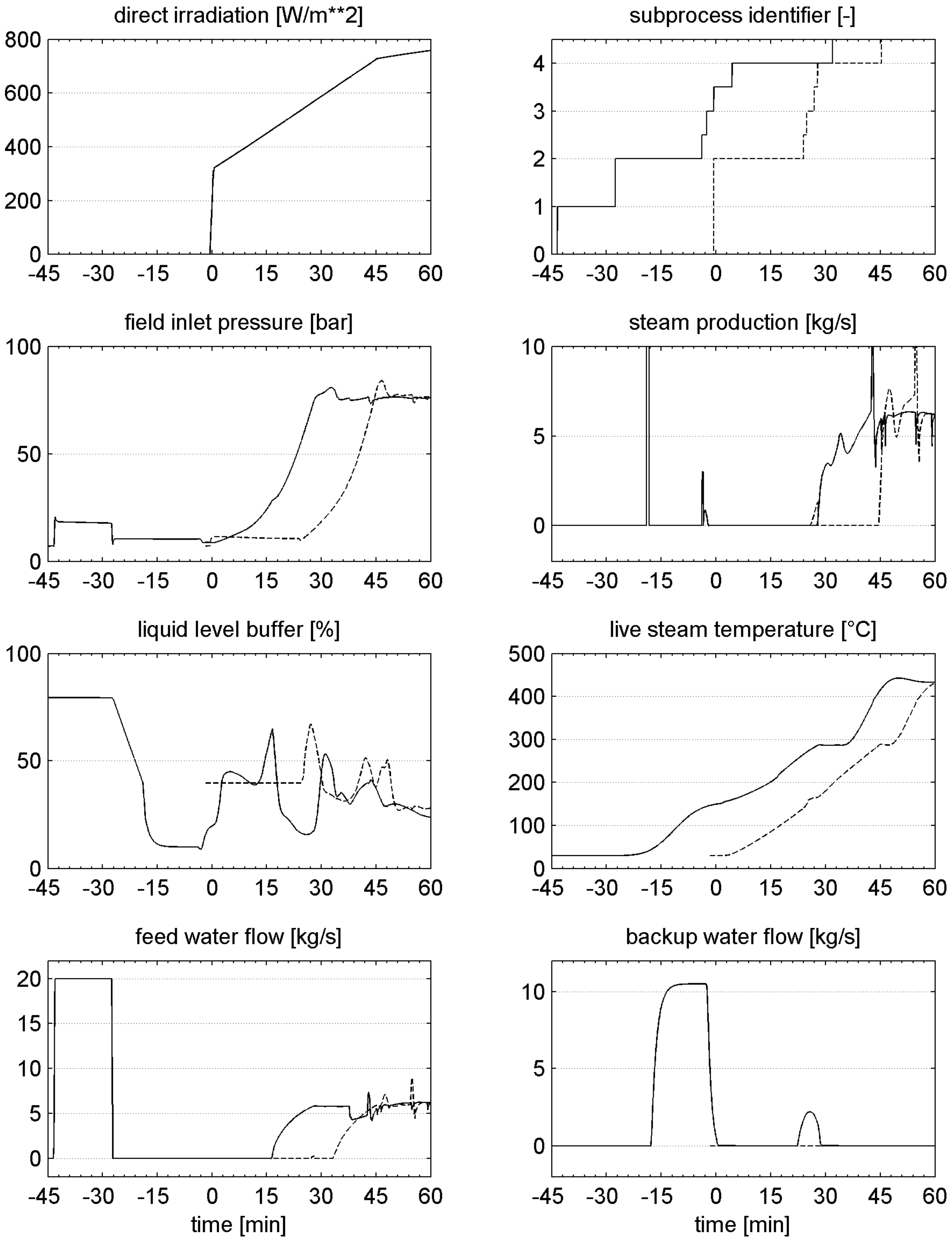

Figure 5: Start-up procedure with pre-heating of the field (---) and solar only start-up procedure (- -)

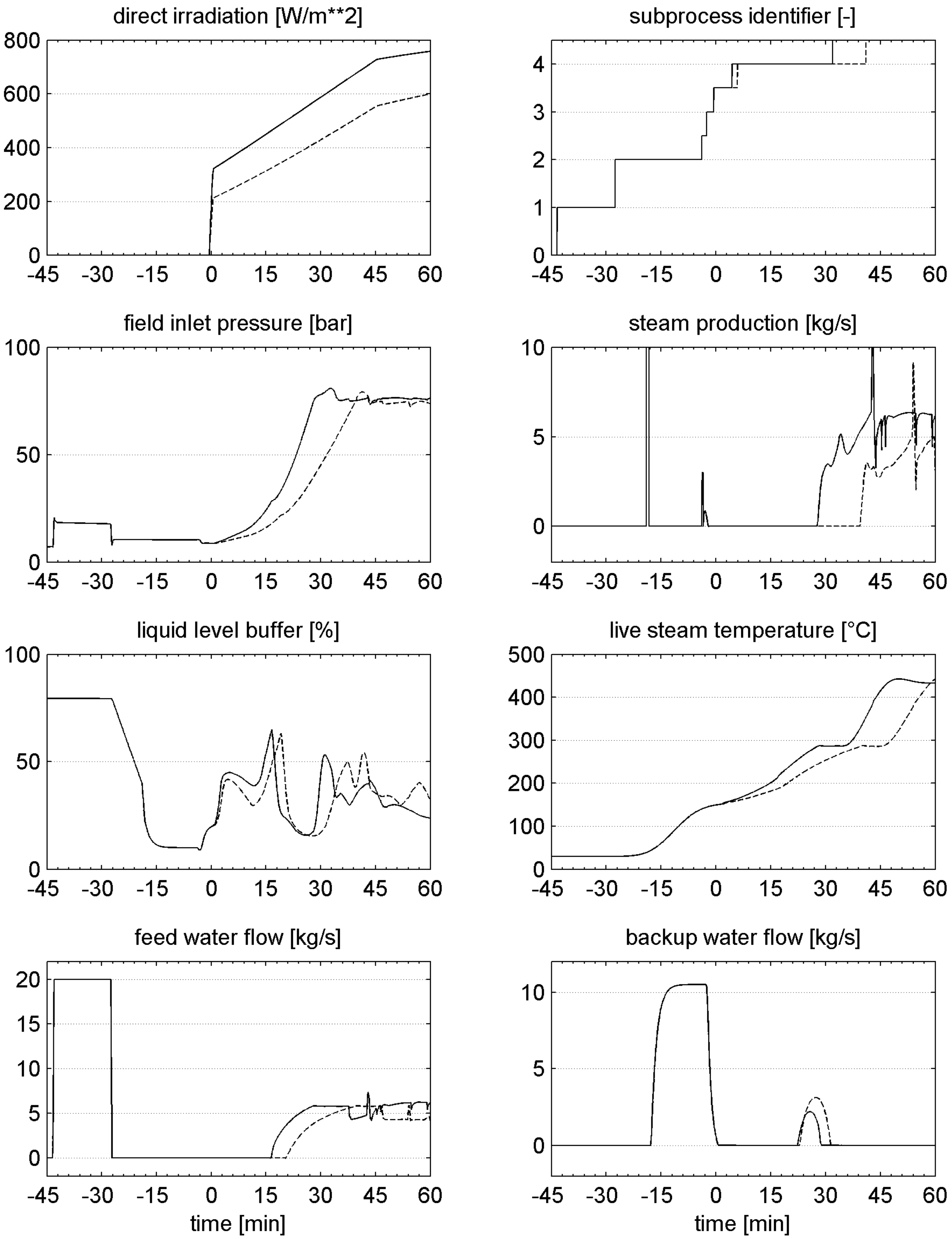

Figure 6: Start-up procedure with clear (---) and turbid (- -) atmosphere.