DYNAMIC SIMULATION OF A SOLAR POWER PLANT STEAM GENERATION SYSTEM

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Abstract

In the frame of the development of new exploitation technologies for renewable energy sources, a steam generation system for a solar power plant has been designed in Germany by Balcke-Duerr. In order to assist the construction of this innovative system, a dynamic simulation of the thermal oil heated boiler has been built by the Vienna University of Technology. Aim of this work is to assess the time needed for the natural water circulation to start and to check if it behaves properly. After a short description of the heat exchanger design, the principles and possibilities of the 2 phase-flow dynamic simulation program APROS are presented. The different stages of the simulation build-up are then described, especially how the discretization of the system has been chosen and which dimensions influence the simulation results most. Further on the different simulated cases are defined as well as the relevant parameters of the system (water circulation direction and rate, oil temperatures, steam mass fraction in water/steam circuit) that are observed during a start-up phase. Eventually the findings related to the simulation build-up and the dynamic behavior of the steam generator are exposed and commented. A design optimization can be carried out with this method.

Keywords: 2-phase flow, dynamic simulation, oil heat exchanger, solar power plant.

Presenting Author’s biography

Thibault Henrion was born in Nancy (France) in 1981. In 2004 he graduates at the École nationale supérieure des mines de Saint-Étienne graduate School of engineering his studies focused on process engineering and energy techniques. After one year further studies in Energy economy and engineering, he moves to Vienna (Austria) where he works two year for OMV as an energy efficiency specialist for the refineries of the group. In September 2008, he starts a PhD project at the Institute of Energy Systems and Thermodynamics in cooperation with Voest Alpine Stahl (Linz-Austria), at the technical University of Vienna. He follows works on one- and two-phase flow in steam boilers as well as in steam distribution systems of iron and steel works.

1 Motivation

In the development phase of a new type of steam generation system dedicated to a solar power plant, a dynamic simulation is necessary for the assessment of transient behaviors of the system. The solar boiler has to be started / stopped every day; this makes of the start-up time one of the main factors influencing the profitability of the unit. It is therefore crucial to evaluate, if during start-up phase the water/steam circulation starts and in which direction. Stagnation or a start with a reverse flow could lead to instability in the water circuit and increase the start-up time. In order to check the ability of the system to be operating as soon as the sun delivers its heating power in the morning or the effect of rapid changes in the solar radiation (clouds, storm), the model has to take into account the thermal inertia of the materials.

2 Description of the Boiler

The principle of the power plant is well known: solar radiation is reflected by mirrors, and focused on an absorber pipe where thermal oil is flowing. It is heated until approximately 400°C. With this hot oil, steam is produced by a heat exchanger. The main new feature of this boiler is an innovative design of the bundle. This advanced solar boiler design (Balcke-Duerr patent) differs from other conceptions; it integrates in one cylindrical frame the three different heat exchanging areas of the steam generation system (economizer, steam generator and superheater). A cross-counter-current flow design is used for the bundles (see Fig. 1).

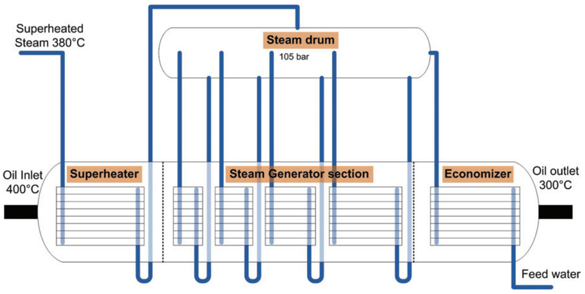

Fig. 1 Schema of the steam generation system

Feed water flows to the economizer part of the boiler where it is heated until short under its boiling temperature. The geometry of the system equipped of a steam drum has been chosen to allow a natural water circulation of the water/steam mixture in the 4 steam generator sections. The produced steam flows from the drum to the superheater where it attains its final temperature of 380°C. At the same time oil is flowing in counter current to the water stream and cools down from 400°C to 300°C.

3 APROS

APROS [1] is a simulation tool which is focused on dynamic simulation of thermal and nuclear power plants. It allows the modeling of 2-phase flow considering each phase separately (6-equation model [2]). A one dimensional discretization method of the pipes is used to solve the governing equations of fluid mechanics [3] [4]. Boiling crisis can be taken into account. The possibilities of varying the models boundary conditions and modeling elaborated control systems makes this program quite appropriate for the purposes of this inquiry.

GRADES is the graphical interface of APROS and allows a process flow diagram representation (see Fig. 2)

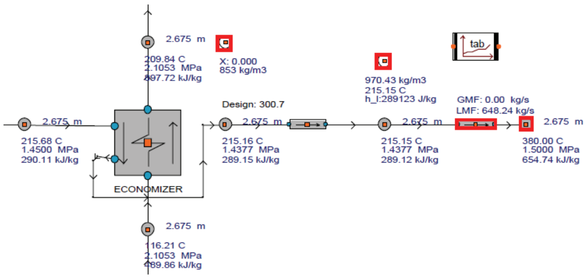

Fig. 2 View of the simulation interface GRADES

4 Modell Build-up

The unit is modeled with the simulation program APROS. The different assumptions and hypotheses taken for the simulation are exposed and discussed in this section.

4.1 Adjustment of oil properties

APROS features a database of different fluids that can be simulated; it includes two different predefined types of oil. This oil model is thought to be used for combustion purposes and not as a heat transport fluid.

The oil database of APROS allows adjustments of the oil properties. The oil properties calculations take as input the density and the dynamic viscosity at 15 and 100 degree Celsius. The APROS calculations of fluid properties have been reproduced in order to adjust the thermal oil parameters (enthalpy, viscosity and density) so that they remain under an acceptable error within the relevant range: 300 to 400°C. Despite adjustments, errors remain significant for heat capacity and heat conductivity. Their influence on the heat transfer coefficients calculations is taken into account in the modeling of the heat exchangers.

4.2 Heat exchanger modeling

The standard module of APROS "counter-current heat exchanger" is used to model the heat exchangers areas. Initially, one heat exchanger is used to model one bundle; it is discretized into 30 nodes to get a high accuracy of the heat transfer calculations. The pressure losses coefficients are calculated and given as model input [5] [6].

After few experiments, the steam generators model accuracy was increased by improving the discretization of the bundle. The tube bank is divided into seven separate heat exchangers discretizising its height. This allows a better modeling of the flow inside the headers, and gives better results concerning the cycle criterion of the steam generators (see explanations in section 5.1).

4.3 Steam drum, header, piping

The piping geometry is exactly reproduced in the model so that the natural circulation of the boiler is simulated with a high definition. Diameters, length, elevation differences and pressure loss coefficients are significant inputs for the different components modeling: downcomers, risers, steam drum. However, few simplifications have been made:

- The steam drum internal components cannot be reproduced with APROS.
- Therefore the elevation of the riser pipes is placed over the water level of the drum so that no steam is entrained in the downcomer pipes.
- An ideal separation of water and steam is simulated in the steam drum.
- All 4 downcomers are connected to the steam drum on the same point.
- All 4 risers are connected to the steam drum on the same point.

4.4 Control system

The numerical simulation of transient processes also requires a precise modeling of the unit control system. Three control loops have been reproduced for the control of the solar boiler during a start-up phase.

- **Steam drum water level control:**

The boiler feed water supply is realized in the model with a pump placed before the economizer. Its rotation speed is controlled in order to adjust the water mass flow so that the water level in the drum attains its set point**.**

- **Steam drum pressure control:**

In order to regulate the steam drum pressure, a valve controls the steam outlet after the superheater. This modeled piece of equipment is comparable with a turbine inlet pressure control valve.

- **Blow down:**

The blow-down of the steam drum is also simulated. A valve regulates the water mass flow that is evacuated from the steam drum, at a constant set point value.

4.5 Boundary conditions

- **Stationary full load**

To validate the boiler design parameters, the unit is first simulated with constant boundary conditions equivalent to full load parameters and brought to a steady state. On the oil side, the oil input temperature, mass flow, and pressure are given as constant boundary conditions. Among the relevant boundaries of the steam/water side, a value is fixed for the feed water temperature and the steam drum pressure set point.

- **Start-up phase**

During the simulation of a start-up phase, the above cited parameters are variable. This can be easily reproduced with APROS by using boundary condition modules. A table of values is given for each boundary varying with the elapsed time of the start-up phase simulation. APROS interpolates linearly between the given points. A characteristic ramp beginning from the initial values ending with the final steady state values is given as input for each 4 variable boundaries: oil mass flow and temperature, steam drum pressure set point and feed water temperature.

The blow-down mass flow is kept constant during the whole simulation.

The steam drum water level is controlled (with the speed controlled feed water pump) thanks to a PID control loop. Experiences show that appropriate control parameters only work for a minimum mass flow of the pump. Therefore, in addition to the formally mentioned boundaries, the feed water mass flow is given as an additional boundary condition during the beginning of the start-up phase. As a consequence, the steam drum water level control loop is put out of order during that time. The feed water mass flow profile is chosen so that the fluctuations of the water level stay under acceptable limits. After approximately the half of the start-up phase, the pump overtakes the control of the steam drum water level.

5 Model validation

The model validation is, combined with the model build-up, an iterative process. In order to reach optimal simulation conditions, the model results are compared with the desired reference data (oil outlet temperatures, preheated feed water and steam flows, superheated steam temperature as well as the cycle criterion). Differences are thus identified and their causes analyzed. Model parameters like discretization precision, heat exchange efficiency (heat transfer coefficient) are responsible for those gaps; they are adjusted in order to get a more accurate answer of the model.

5.1 Full load behavior

First of all, the design conditions of the unit are programmed in the APROS model. This simulation corresponds to a full load operation case.

- **headers dicretization**

In a first step, each heat exchange area (steam generators, superheater, and economizer) is simply modeled in APROS with one heat exchanger module with a maximum of discretization nodes. The Simulation shows sensible differences between the simulated and design steam generators cycle criterions values. Further simulations show that the influence of pressure losses coefficients of the downcomer and riser is not significant enough to explain the differences. The size of the header is identified as the main factor influencing natural convection flows. Therefore the accuracy of their modeling has been increased in separating the steam generator in several layers, each simulated each by one heat exchanger module (see Fig. 3).

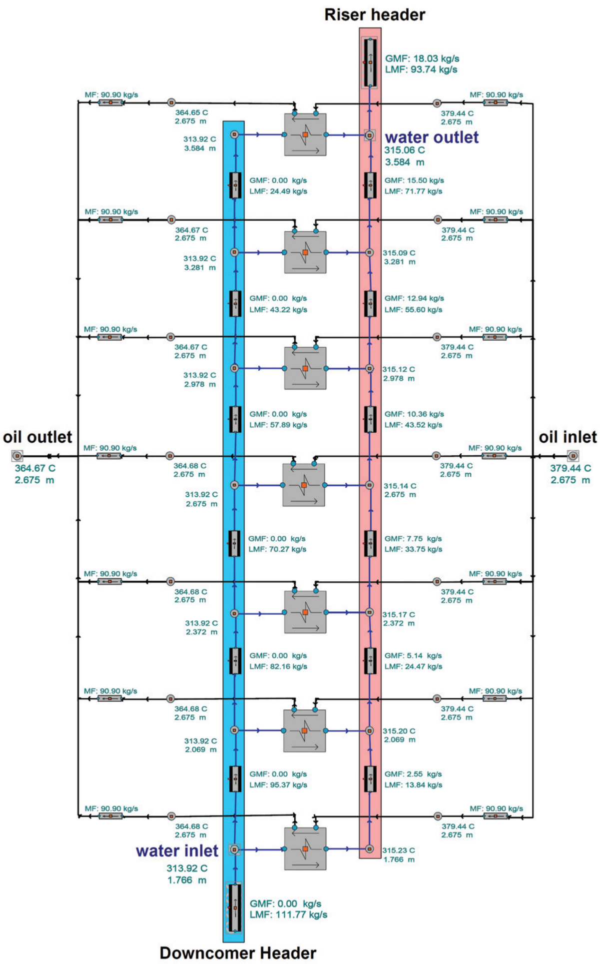

Fig. 3: layer discretization of steam generator 1

The steam/water mass flow inside the headers within the bundle can be more accurately calculated in that way. With increasing elevation, the downcomer header mass flow decreases and the riser header mass flow increases. With the new discretization, this behavior of the headers is better taken into account as pressure losses are estimated with more accuracy.

Tab. 1 and Tab. 2 show significant better values for the downcomer water flow and the cycle criterion of the modeled heat exchangers with the improved discretization.

Tab. 1: Influence of steam exchanger discretization on cycle criterion

	Cycle criterion		
	Design [1]	Model [1]	Model improved [1]
Steam Generator 1	*7.371*	5.827	6.207
Steam Generator 2	*6.848*	5.957	6.336
Steam Generator 3	*6.543*	5.667	6.055
Steam Generator 4	*5.717*	5.978	6.364

Tab. 2: Influence of steam exchanger discretization on downcomer water flow

	Downcoming water flow		
	Design [normed]	Model [normed]	Model improved [normed]
Steam Generator 1	*128.26*	104.47	111.78
Steam Generator 2	*119.16*	102.87	109.87
Steam Generator 3	*113.85*	101.39	108.68
Steam Generator 4	*99.48*	96.49	103.09

The average errors between the design values and the original model results are 13% for the cycle criterions and 11,5% for the downcomer water flows. Between design values and the improved model, we calculate errors from 10,5% for the cycle criterion and 7,2% for the downcomer water flow. This comparison shows a significant improvement of the model accuracy.

- **heat transfer coefficients correction**

As differences remains between the real oil properties and the modeled ones, a correction factor is affected to the oil side heat transfer coefficients in the APROS heat exchanger modules. In order to assess the error induced by the properties deviance, two heat transfer coefficients are calculated separately with the real oil data and the APROS simulated ones. Equation (1) from [8] and equation (2) from [5], [7] are used for the evaluation of the Nusselt characteristic number giving the bundle heat transfer coefficient.

(1) – Dittus Boelter

$$Nu_{Bundle} = 0{,}023 \cdot \mathrm{Re}_d^{0{,}8} \cdot \mathrm{Pr}^{0{,}4} \tag{1}$$

Where Re_d is the Reynolds number calculated with the pipe diameter

(2) - Gnielinski

$$Nu_{Bundle} = \left(0{,}3 + \sqrt{Nu_{l,turb}^2 + Nu_{l,lam}^2}\right) \cdot f_a \tag{2}$$

Where f_a is a factor depending on the bundle tubes arrangement,

$$Nu_{l,lam} = 0{,}664 \cdot \sqrt{\mathrm{Re}_{\psi,l}} \cdot \sqrt[3]{\mathrm{Pr}}\ ,$$

$$Nu_{l,turb} = \frac{0.037 \cdot \mathrm{Re}_{\psi,l}^{0,8} \cdot \mathrm{Pr}}{1 + 2{,}443 \cdot \mathrm{Re}_{\psi,l}^{-0,1} \cdot \left(\mathrm{Pr}^{2/3} - 1\right)},$$

Pr is the Prandtl number,

$\mathrm{Re}_{\psi,l}$ is a Reynolds number calculated with the equivalent length $l = (\pi/2) \cdot d$, the velocity before the tube bank and corrected with the factor ψ depending on the bundle tubes arrangement.

Both calculations give comparable differences between heat transfer coefficients. The calculated differences with the Gnielinski correlation are used as correction factors (see Tab. 3)

Tab. 3: correction factors and resulting heat transfer coefficients on the oil side used in APROS

	correction factor [%]	α_oil_average [W/m².°C]
Superheater	125.8%	1627.4
Steam Generator 1	128.3%	1630.9
Steam Generator 2	128.9%	1603.8
Steam Generator 3	128.7%	1572.5
Steam Generator 4	130.6%	1534.6
Economizer	135.4%	1528.6

The heat transfer coefficients on the water side are always greatly higher than these on the oil side. The oil side coefficients are therefore determining for the heat transfer.

With these rating of the simulated heat exchangers, only small deviance is observed between simulation results and the design values as Tab. 1 shows for steam generators cycle criterion and Tab. 4 for economizer and superheater parameters.

Tab. 4: Validation Superheater and economizer

		Superheater		Economizer	
		Design	Sim. APROS	Design	Sim. APROS
Oil Temp. before HX	[°C]	393.00	393.00	320.60	320.10
Oil Temp. after HX	[°C]	379.56	379.44	300.70	300.32
w/s Temp. before HX	[°C]	315.03	314.18	228.00	228.00
w/s Temp. after HX	[°C]	381.00	384.35	310.00	308.37

- **fouling**

Two factors are considered to explain the gap between the simulated heat transfer coefficients and those used in design calculations.

On the one hand, APROS calculates the heat transfer coefficients with Dittus Boelter correlation; this equation (1) gives slightly lower coefficients than the Gnielinski equation (2), which was used by Balcke-Duerr for the design calculations. On the other hand, fouling factors were taken into account in the design calculations, which decrease the heat transfer efficiencies. The good convergence of the full load steady state simulation and the design parameters (on Tab. 4) shows that these both deviations are compensating each other. A comparison of the total heat transfer coefficients in Tab. 5 confirms the small differences between APROS simulation and Balcke-Duerr hypotheses. There is no need to further correct the heat transfer coefficients of APROS.

Tab. 5: Validation of total heat transfer coefficient

	APROS [W/m².°C]	Balcke-Dürr design [W/m².°C]
Superheater	1053.0	898.0
Steam Generator 1	1478.6	1323.0
Steam Generator 2	1457.6	1323.0
Steam Generator 3	1404.8	1323.0
Steam Generator 4	1366.7	1323.0
Economizer	1239.1	1222.0

Conclusion

This validation of the model shows that, with an iterative process, a good approach of the design parameter is possible. However, the header dimensions are a limiting factor for the natural circulation in the evaporators.

5.2 Start-up phase validation

The next step consists in comparing the start-up simulation results of the boiler with scaled data from another existing unit (reference data), however, with slight constructive differences.

- **Initial conditions**

Before the start of the unit, no oil or water is flowing, and both are in thermal equilibrium at approximately 200°C. In the steam/water circuit, saturation conditions are simulated. The heat exchangers wall material is also in thermal equilibrium with both fluids at 200°C.

- **Validation**

As mentioned in 4.5, the variable boundaries are applied along the whole start-up phase. The results of the simulation are then compared to the reference data

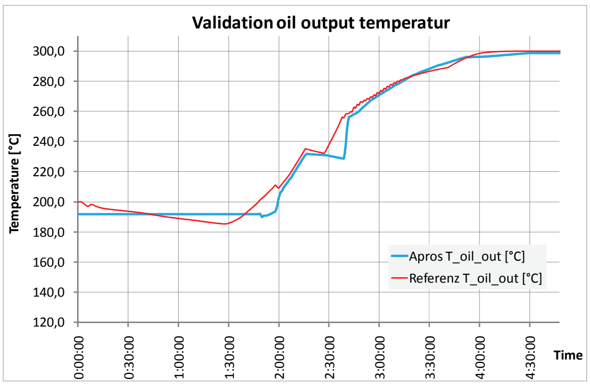

Fig. 4: oil outlet temperature

Fig. 4 shows a good convergence of the predicted oil outlet temperature between the simulation and the reference data (+/- 5°C) except for 2 areas at 1:50 and

2:40. Inconsistencies in the reference data are responsible for these gaps.

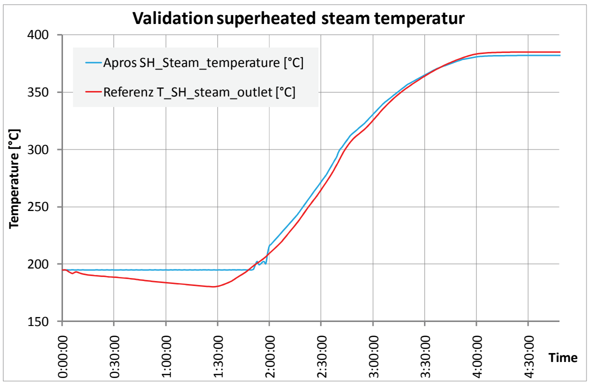

Fig. 5: Superheated steam temperature

In Fig. 5 we also observe a good alignment of the model with the reference. Differences on the overheated steam temperature hardly exceeds +/-5°C.

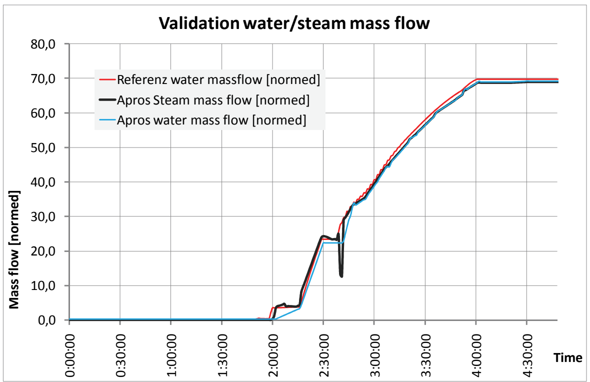

Fig. 6: Steam/water mass flow

On Fig. 6 the profiles of the simulated water and steam mass flows are also following with a good accuracy the reference. The gap at about 2:40 is due to inconsistencies in the reference data. The control loop of the feed water supply is responsible for the small fluctuations of the APROS water flow between 3:00 and 4:00.

An iterative process was also necessary to find the optimal feed water flow profile, so that the steam drum level stays within acceptable range during the start up phase, before feed water pump regulation loop is activated. The adjustment of the feed water pump control loop parameters was also made iteratively.

Conclusion

The validation results show very good convergence between simulation and reference data, even if few differences remain. These gaps can be explained by non optimal control loop parameters or inconsistencies in the reference data. Considering these results, the simulation should be able to deliver reliable results concerning the inquiry on start time.

6 Simulation findings

6.1 Boiling in the economizer

The registered data from the start-up simulation (see Fig. 7) show that boiling occurs in the economizer part of the system over a period of the start-up phase.

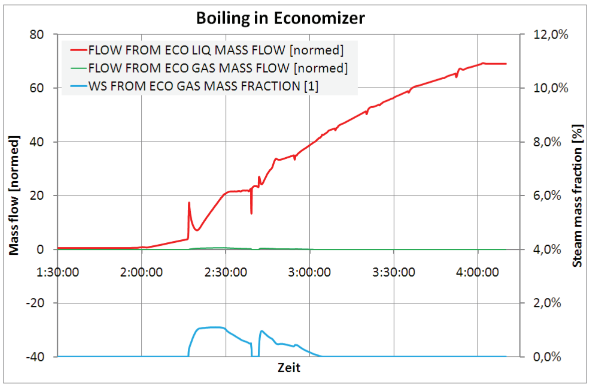

Fig. 7: Economizer parameters over start-up

In Fig. 7, we observe a vapor mass fraction reaching until 1% in the flow coming out of the economizer. This phenomenon lasts from about 2:15 to 3:05. This finding is not unusual for a steam generation system.

Beside that fact, the simulation also shows that, in normal operation, water is approximately 6°C undercooled as it leaves the economizer (see Tab. 4), which is a conventional value for such a unit.

These findings give an advice that attention should be paid, by the steam drum design. Actually, the steam produced in the economizer during this transient phase should not flow into the downcomer pipes. This could affect the natural circulation of the boiler. In order to avoid this undesirable situation, internal components can be build inside the steam drum to enhance the vapor separation or/and a certain elevation and space gap should be maintained between the downcomer and the economizer pipes drum connections.

6.2 Start of the natural circulation

The observation of the water and steam mass flows in the downcomers entering the steam generators and in the risers flowing out of them, allows us to analyze the circulation inside the steam generators.

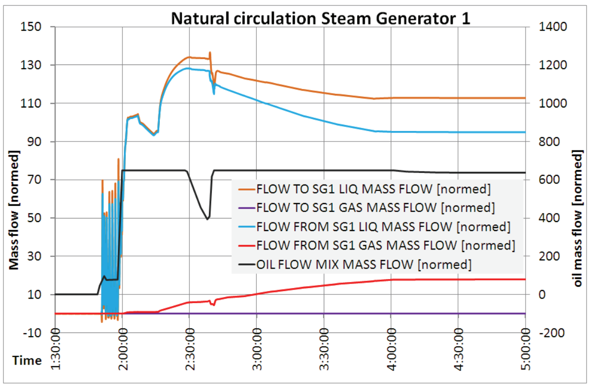

Fig. 8: Natural water circulation in Steam generator 1

During the unit start-up, we observe that the circulation begins oscillating in first steam generator (see Fig. 8). As it is started at approximately 2:00, the circulation stays stable until the rest of the start-up phase. Especially when abrupt disturbances of the oil heat input happens (fall-off of the oil mass flow followed by a steep increase of the oil mass flow combined with a steep increase of the steam drum pressure at about 2:40), simulation shows (Fig. 8) that the circulation is not seriously affected. This highlights a robust natural circulation

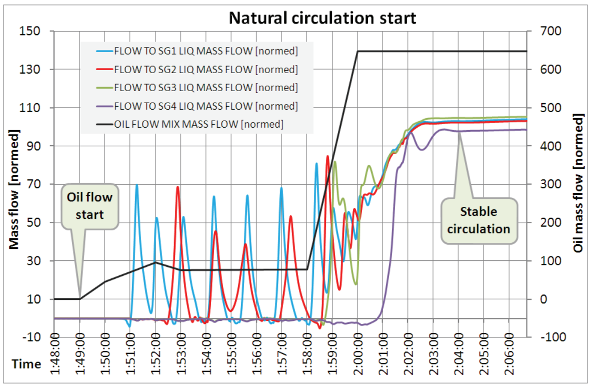

Fig. 9: Natural circulation start

The Fig. 9 represents the water flows in the downcomers of all 4 steam generators. It shows a more detailed picture of the natural circulation start. We observe that the circulation starts with oscillations in steam generator 1 and 2, when the oil mass flow remains small (low heating power). But, from the moment the oil heating power gets rapidly higher at 1:58, it stabilizes quite quickly.

On the same Fig. 9, we clearly observe for the steam generator 4, that temporarily a small negative circulation mass flow sets up.

In order to inquire this short phase more precisely, Fig. 10 zooms on the circulation start of the 4th steam generator.

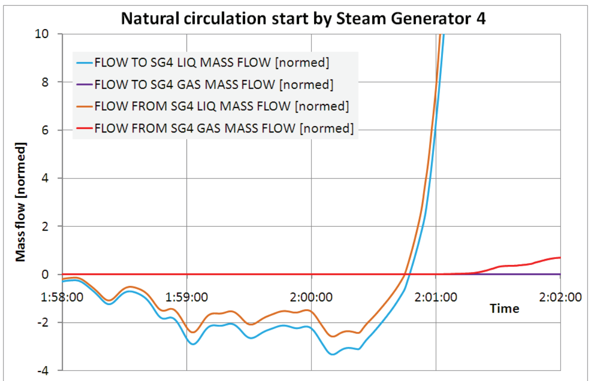

Fig. 10: Natural circulation start by steam generator 4

We observe in Fig. 10 that in both riser and downcomer a very small water mass flow sets up for a short period of about 180 seconds. This reverse flow is not disturbing for the operation of the unit for several reasons:

- Only water is flowing in reverse flow.
- Steam flow is registered in the riser after the flow returned in the positive direction (at about 2:01:30).
- No steam flow is registered in the downcomer

Conclusions

We can conclude from the simulation results that the natural circulation is stable as soon as the heat flux is sufficient. For the simulated start-up phase, the natural circulation starts rapidly in the steam generator heat exchangers; within 15 minutes after the beginning of oil circulation. Small negative water flow can transitionally occur in the last steam generator, however this mass flow reverses as soon as steam is produced and do not represent any danger for the proper operation of the unit.

7 Conclusions and perspectives

With the help of APROS, it was possible to build-up and validate the dynamic simulation of a thermal oil steam generation system. Therewith an analysis of the equipment behavior during a start-up phase has been carried out before its construction. The results are consistent with design calculations and allow its further optimization. These numerical inquiries reveal that boiling occurs in the economizer during the start-up phase. This phenomenon can be controlled throw simple construction precautions. The APROS simulation highlights that for this integrated boiler design the natural circulation begins within short time and also shows that this conception could fulfill the operation requirements of a solar power plant.

After the real construction of the analyzed system, the model could be further improved, by validating it with process data, in order to get a better accuracy of the simulation. To a larger extent, it is also possible thanks to the automation tools box of APROS to carry out some safety analysis (simulation of an emergency shut-down), tests and optimization on some control loops parameters, or even build-up a simulator of the unit dedicated to operator training.

8 References

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