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# Volume Changes in DSG Solar Field and Steam Drum due to Changes in Evaporation Conditions from Experience

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**Abstract.** For process heat supply the integration of solar direct steam generation can be a significant fuel saver. Since 2015 an Industrial Solar GmbH solar field demonstrates safe operation and stable steam supply at the RAM Pharma pharmaceutical company. One mayor component is the steam drum, which buffers volume changes due to evaporation and condensation in the solar field. Operational data of almost two years is analyzed to understand level changes in the steam drum and draw conclusions regarding operation of direct steam generation installations with recirculation concept and to improve the future layout.

## INTRODUCTION

At the Jordanian pharmaceuticals manufacturing company RAM Pharma, a direct steam generation (DSG) solar field supplies saturated steam at 6 $bar_g$ as solar process heat [1]. The collector field consisting of 394 m² of linear Fresnel collectors (Fig. 1) has been constructed by Industrial Solar GmbH in March 2015 and operated since then. In the frame of the SolSteam project, an extensive amount of operational data is being analyzed by the partners. A safe operation and stable steam supply where demonstrated [2].

**FIGURE 1.** Collector Field and Steam Drum on the RAM Pharma Rooftop

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In this paper the measured volume changes in the steam drum are analyzed to evaluate the typical layout. This approach is similar to [3] but in this case applied to a solar process heat plant instead of a power plant. In general to dimension the steam drum, the volume of steam filled piping is calculated. This volume needs mostly to be filled from the water content in the drum when clouds appear and vice versa the drum needs to be able to take the flush of water appearing when evaporation starts.

## MASS BALANCE OF THE STEAM DRUM

In the recirculation concept of Direct Steam Generation (DSG), liquid water is pumped from the steam drum to the solar field, where it is first preheated and then evaporated partially. The mixture of liquid and steam flows back to the steam drum, where it is separated. The saturated steam leaves the steam drum towards the costumer's steam network. To maintain a constant water mass within the solar field and steam drum circuit (Fig. 2), the equivalent mass flow of feed water has to enter the steam drum.

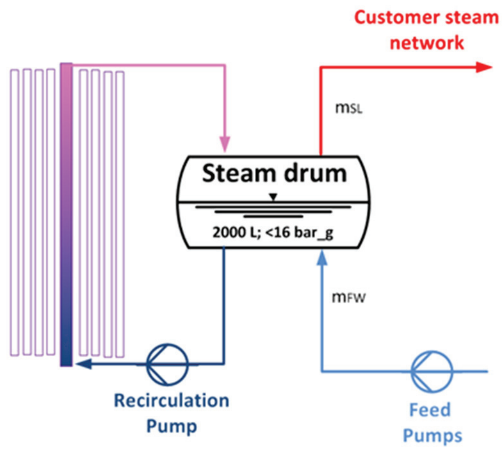


**FIGURE 2.** Schematic mass balance of steam drum

During nominal, stable operation the mass flow to the solar field equals the mass flow out of the solar field. A difference between feed water mass flow and steam mass flow directly leads to a change in the steam drum level, as displayed by the calculated values (dashed line) in Fig. 3.

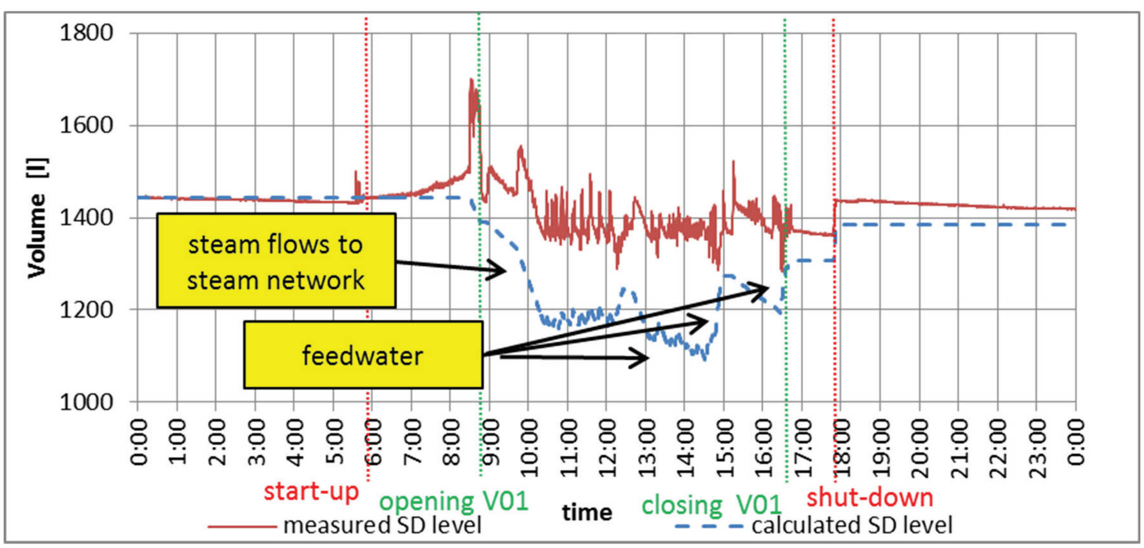


**FIGURE 3.** Diagram of the measured and calculated steam drum level in comparison (13th of July 2016)

As an example, the measured steam drum level data of July 13th in 2016 are shown in Fig. 3 in comparison to the level calculated from the mass balance. A comparison between the calculated and measured steam drum level reveals that the water volume is shifted to the steam drum during evaporation and that the water volume is shifted back to the solar field during condensation in the solar field. This effect is due to the considerable difference in densities of liquid water and steam.

## Measurement Uncertainties

In the following the uncertainties of the flow meters are discussed. The feed water mass flow is measured by a magnetic flowmeter. The manufacturer indicates an uncertainty of 0.2 % of the measured value +1 mm/s. The steam mass flow is measured with a steam flowmeter operating on the target principle. For the applied diameter and pressure it functions within a range of 46 to 460 kg/h. The manufacturer indicates an uncertainty of 2 % of the measured value for measured values bigger than 20 % of the maximum Value (460 kg/h) and 2 % of the maximum value (9.2 kg/h) for measured values smaller 20 % of the maximum value. Therefore the uncertainty of the steam mass flow measurement is bigger than the one of the feed water measurement. Subtracting the maximum steam flow from the minimum feed flow, results in the minimum calculated steam drum level. Similarly subtracting the minimum steam flow from the maximum feed flow, results in the maximum calculated level. Both are indicated in dotted lines in Fig.4. Since the uncertainties in the flow measurements add up to the level over the day, the minimum calculated SD level and the maximum calculated steam drum level spread further apart in the course of the day. In the end of the day the measured level is closer to the level calculated without consideration of the flow measurement uncertainties. The qualitative conclusions of the comparison from measured and calculated level remains unaffected by the uncertainties, therefore the uncertainties are neglected in the following.

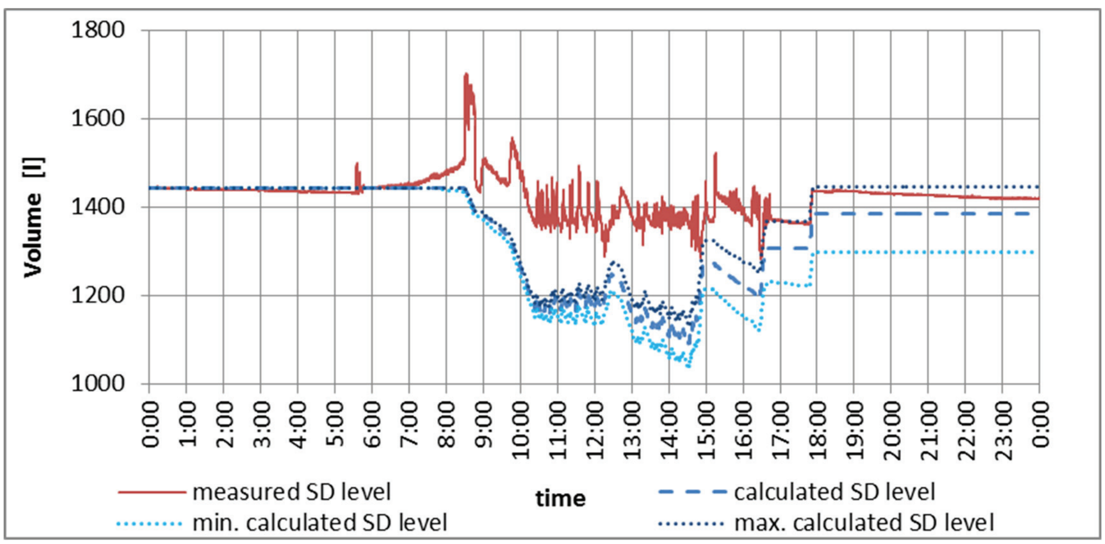


**FIGURE 4.** Diagram of the measured and calculated steam drum level in comparison containing flow meter uncertainties (13th of July 2016)

## ANALYSIS OF THE CHANGING CONDENSATE VOLUME IN THE STEAM DRUM DUE TO EVAPORATION OR CONDENSATION IN THE SF

To be able to analyze the level changes due to evaporation and condensation, the measured level is subtracted by the level calculated from the measured mass flows, as displayed for the 13th of July 2016 in fig.5. In Figure 5 the SD pressure and the opening of the steam valve are displayed, to analyze their influence on the changes in steam drum level due to evaporation and condensation in the solar field and in the steam drum. With knowledge of the operation strategy of the plant the diagram is structured in 7 phases, which are described and discussed in the following.

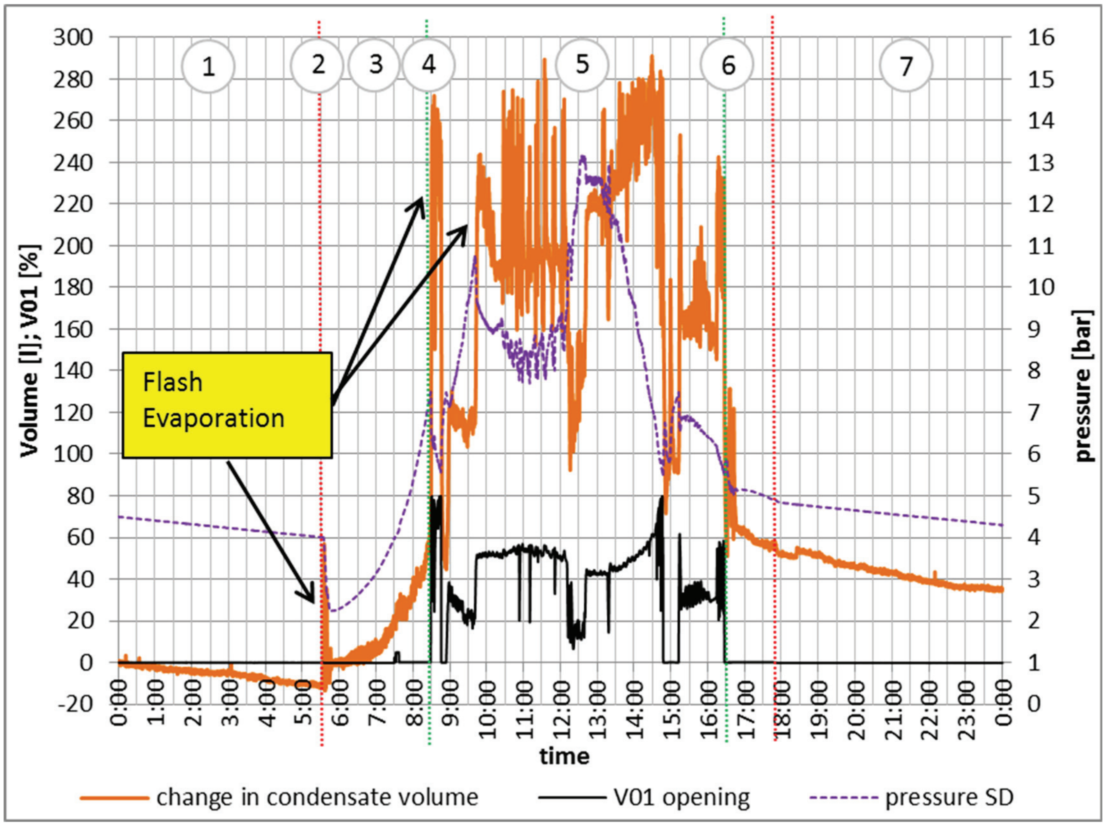


**FIGURE 5.** Diagram of the changes in condensate volume in the steam drum (13th of July 2016)

1. In the morning while the solar field is still defocused and the pumps are not operating, the level in the steam drum drops by about 2 l/h. The solar field cools down and its thermal expansion decreases. Therefore the volume in the solar field decreases and is replaced by water from the steam drum.

2. At about 05:30 the recirculation pump is switched on and the solar field starts to focus. Cold water from the solar field and piping is pumped into the hot steam drum, where it suddenly reduces the temperature and therefore the system pressure and the evaporation point by 1.5 bar. At the same time hot water from the steam drum is pumped into the solar field, where the temperature increases from about 85 °C to 140 °C and exceeds the evaporation point. The suddenly expanding steam pushes a water volume of about 66 l into the steam drum. But since at this time the solar power entering the system is low, the steam bubble directly collapses and the steam drum level decreases.

3. As the sun rises, more and more power enters the solar field and is transferred to the liquid which evaporates. The system pressure as well as the steam drum level increase. The increasing steam content of the solar field displaces 60 l water in a period of 2 hours into the steam drum.

4. When the pressure in the steam drum reaches the opening pressure of the steam valve around 08:30, the steam valve suddenly opens 80 % and a steam flow to the consumer reduces the system pressure by 1.7 bar. The pressure drop decreases the evaporation point and therefore causes a flash evaporation. This increases the steam drum level by 207 l within about one minute.

5. During normal operation the level of the steam drum depends on the pressure in the steam drum, which results from the entering solar power and steam demand. Because the solar power was relatively stable on the 13th of July 2016, the level in the steam drum follows the opening of the steam valve V01, which represents the demand profile. When the demand increases, the opening of V01 increases and the pressure drops, therefore the level increases. This inversely proportional correlation between steam drum pressure and steam drum level can only be explained by flash evaporation. The system remains in saturation condition. Each pressure drop increases the steam phase in the solar field, which pushes water into the steam drum. For example on the 13th of July at 10:30, because of the high pressure level, the opening of the steam valve for 4 % causes a pressure drop of about 0,7 bar, which again causes an increase in the steam drum level of about 100 l.

6. Vice Versa, an increasing pressure leads to a collapse of the steam bubble as soon as the evaporation temperature exceeds the actual temperature. Therefore the level decreases when the steam valve is closed at 16:30, for 160 l in 3 min.

7. After the steam valve was closed and the mirrors are defocused the pressure and the level in the steam drum drop again slowly, because the condensate in the solar field cools down and its thermal expansion decreases. The volume is replaced with liquid from the steam drum. Initially about 10 l/h are moved from the steam drum to the solar field, over night the rate decreases related to temperature.

One more cause for a decrease in level is a decrease in solar field temperature due to cold feed water entering, which was observed on other days, but not on the 13th of July. The installed feed water pump has to overcome a big pressure drop and therefore is oversized with regard to the steam mass flow. Therefore it does not continuously supply feed water to steam drum but delivers intervallic peaks. The feed water comes from a tank in which hot condensate from the steam network of the consumer and cold make up water mix. The temperature of the feed water tank is not controlled. During a day of high consumption the feed water has a high temperature and does not influence the evaporation in the solar field as strong as after periods of low consumption, when the feed water is cold and the comparatively high feed water mass flow cools down the water entering the solar field and stops the evaporation.

Over the day the level increased and decreased by about 250 l, independent from the water fed in or out, only because of the difference in density between liquid and steam.

These 7 phases are recognizable every day, but the amplitude of volume changes can differ significantly. Figure 6 shows these amplitudes for three of the seven phases for nine random days. The startup of the recirculation pump (phase 2) always causes an increase in level, but while on the 19th of April 2017 only 50 l were shifted to the steam drum, about 220 l were moved on the 24th of October 2016. While on many days the flash evaporations of startup and V01 opening cause higher peaks in the steam drum level than the energy increase in phase 3, there are some days, when the energy increase causes a higher level increase like for example on the 28th of July 2016. And although the level increases of startup and during the increasing energy are moderate on the 13th of July 2016, opening V01 causes a level increase of more than 200 l.

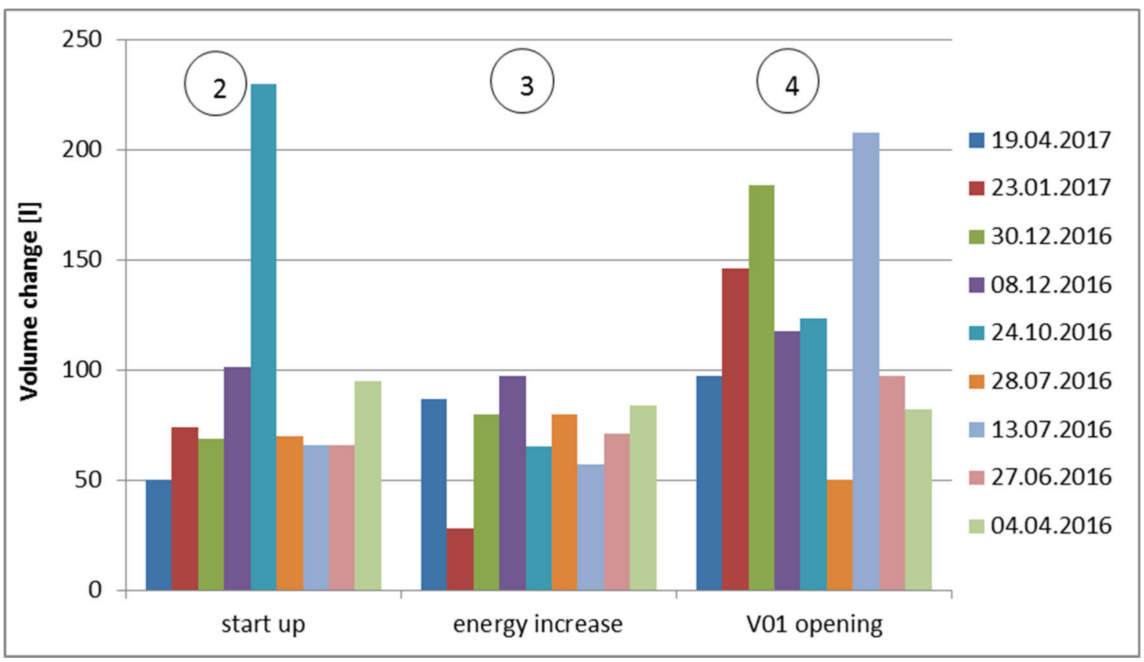


**FIGURE 6.** Comparison of the changes in condensate volume in the steam drum for 9 exemplary days

Evaporation can start the earliest at the inlet of the absorber tube. The water mass from the inlet of the absorber tube to the inlet of the steam drum, for a completely filled piping is 283 kg. Hence, a maximum of 283 kg water can maximally be shifted to the steam drum during evaporation. The corresponding level change is temperature dependent. The calculated maximum increase in SD volume of 327 l corresponds to the maximum SD temperature of 189 °C. During the observed changes in SD volume a maximum of 70 % of this Solar field water volume was shifted to the steam drum.

**TABLE 1.** Causes for increases and decreases in the steam drum level

| Level Increase | Level Decrease |
|---|---|
| Feed water increases water mass | Steam flow to the consumer reduces water mass |
| Evaporation in the solar field due to an increase in power, temperature and pressure | Condensation in the solar field due to a decrease in power, temperature and pressure |
| Flash evaporation in the solar field due to an (increased) opening of V01 and a related pressure drop | Collapse of the steam bubble in the solar field due to the decrease in temperature caused by evaporation, or due to an increase in pressure without an increase in power. |
| Shrink and swell effect due to flash evaporation in the steam drum due to opening of V01 and a related pressure drop | The feed water mass flow cools down the solar field and stops evaporation. |
| Thermal Expansion in the liquid water due to temperature increase | Temperature decrease causes liquid water volume to shrink |

Analyzing the extensive amount of operational data from the direct steam plant in Amman, different causes could be identified for increases and decreases in the steam drum level, which are listed in Table 1.

Some of the causes are equivalent, others are contrary. While it is obvious, that the steam drum level increases when its water mass is increased by feed water in contradiction the feed water can also decrease the level, when it cools down the solar field until the evaporation stops and the volume of the decreasing steam phase in the solar field is replaced by water from the steam drum. Depending on the temperature of feed water, this effect can balance or even exceed the effect of added water mass.

Also a pressure drop due to a decrease in incoming power causes a decrease in evaporation and therefore a decrease in the steam drum level. But in contrary a sudden pressure drop due to an opening valve or a decrease in temperature, with a constant incoming power, causes flash evaporation and therefore an increase in level.

## CONCLUSION FOR OPERATION AND FUTURE STEAM DRUM DESIGN

The steam drum installed at RAM Pharma was designed to also function as a Ruths storage with a capacity of 2000 l to buffer clouds and therefore is very big in comparison to the shifted water volumes of up to 230 l. Therefore the control of the steam drum level is not challenging. Feed water control simply has to guarantee, that the steam drum level always remains in the wide range in between the boundaries of about 300 l to 1700 l. The implemented feed water control even manages to keep the level fairly stable at around 1500 l. An improved level control could increase the Ruths storage capacity by elevating the water level to around 1700 l. It should consider the daily level profile and start with a lower level of about 1500 l in the morning to provide enough space for the water shifted during evaporation during start up and the opening of the steam valve and provide a higher level during operation, to be able to replace steam volume in the solar field during condensation because of transients and shut down. To prevent the evaporation from collapsing by cold feed water, a more continuous but therefore smaller feed water mass flow could be realized with a bypass.

Evaluation of the operational data confirmed the conventional layout strategy to design the steam drum as big as the water volume of the solar field.

## SUMMARY

Solar fields with direct steam generation in the recirculation concept use a steam drum to buffer volume changes due to evaporation or condensation in the solar field. Due to the significantly lower density of steam, an increase in the steam phase in the solar field is accompanied by an extensive increase in Volume, which pushes remaining liquid in the piping into the steam drum. Vice Versa a decreasing steam phase reduces the Volume of the water in the solar field and draws back liquid from the steam drum into the solar field. From the analysis of the operation data of a process steam plant at RAM Pharma built by Industrial Solar GmbH seven phases where identified in which the level changes during the day. The biggest changes in steam drum level are usually caused by starting the recirculation pump in the morning (2), opening the steam valve (4) and closing the steam valve (6). Between 50 l and 250 l are usually moved between solar field and steam drum due to the density difference. Since the installed steam drum has a capacity of 2000 l, this level changes are easily manageable.

## ACKNOWLEDGMENTS

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