

# Evaluation of Flow Patterns for Direct Steam Generation

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**Abstract.** In solar Direct Steam Generation (DSG) systems, steam is produced directly in the solar field instead of producing it in a steam generator. Liquid water is fed to the solar field and is heated as it flows through the absorber pipes until it starts to evaporate and a two-phase flow develops. The resulting two-phase flow can take various forms, such as slug flow or annular flow, depending on the vapor content and other influencing variables such as the mass flow through the absorber tubes. There are flow patterns that are unfavorable for the operation of a solar thermal system. In particular, a stratified flow with a high vapor content can lead to the formation of dry areas in the upper inner walls of the absorber tube. At these areas, the heat can no longer be sufficiently transferred to the liquid, so that the wall temperature rises and the tubes can become deformed leading to the breakage of the glass cover [1,2,3,4]. In addition, further mechanical loads can be added by the momentum inherent in the slug flow. The annular pattern is a particularly advantageous flow pattern for direct evaporation. In this case, the liquid flows as a ring along the wall through the absorber tube, while the vapor flows inside the liquid. This ensures that the heat is absorbed evenly by the liquid. In the Jordan Optimizing Solar Steam for Industry (JOSSI) project, a measurement campaign was carried out with the aim of recording the two-phase flow patterns within the horizontal absorber tubes and investigating their occurrence under different operating conditions.

**Keywords:** Direct Steam Generation, Process Heat, Two Phase Flow

## 1. Measurement campaigns

The measurement campaign took place from October 6 to 7, 2023 at the Fresnel solar plant in Amman, Jordan. The plant is located on the roof of the company JTI (Japan Tobacco International), which uses the steam for its processes. A total of 38 operating points was investigated in order to observe the effects of different operating conditions on the two-phase flow pattern. Quasi-stationary and transient operating conditions were investigated by adjusting the setpoint of the steam drum and the mass flow as well as moving collectors in and out of focus.

### 1.1 Plant Design & Measurement Setup

Figure 1 shows a view of the solar field. The solar field consists of three parallel rows of collectors, which contain 19 Fresnel collector modules per row. The total primary mirror area of

the solar field 1254 m<sup>2</sup>, resulting in a total peak thermal power of 700 kWth [1]. The solar system operates according to the principle of Direct Steam Generation (DSG), in which water is heated as it flows through the absorber tubes and is evaporated once the saturation temperature is exceeded. This results in a two-phase flow that can take various forms, which will be discussed further in section 2.



**Figure 1.** Bird's eye view of the Fresnel solar system (Photo: Industrial Solar GmbH)

During operation, all system parts are continuously monitored by an extensive set of pressure, flow and temperature sensors to determine the operational state of the system. In addition, a tracking pyrheliometer and two pyranometer are used to measure DNI and global and diffuse irradiation respectively. The data of all these sensors are continuously logged with a resolution of one second. In order to determine the two-phase flow patterns inside the absorber tube, a wire-mesh sensor developed by HZDR was installed, this unique measurement system is ideal for determining the flow pattern at the exit of the solar field and was also used before in a smaller installation by the authors [5]. Moreover, a vibration sensor is also installed at the exit of the solar field in order to assess the relationship between vibrations and two-phase flow pattern.

## 1.2 Wire-mesh sensor design and measurement principle

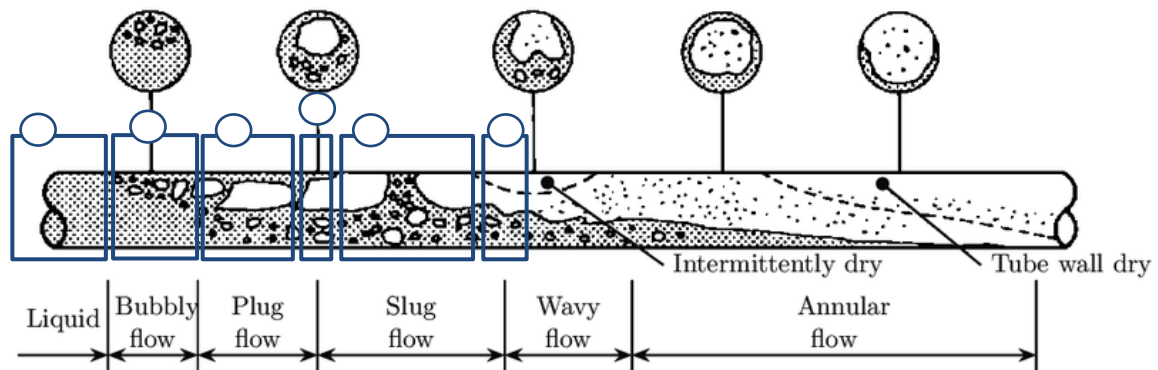
The wire-mesh sensors (WMS) measurement principle relies on fast local instantaneous measurements of the fluid conductance in a multitude of small measurement points distributed over the cross section of the pipe. Therefore, a grid like structure is built by two planes of parallel stretched wire electrodes oriented perpendicular to each other with a small axial gap. While one plane acts as the transmitter plane, where the single wires are activated sequentially with a  $\pm 3$  V bipolar excitation signal of 6  $\mu$ s period length, the receiver wires in the other plane are measuring the resulting current transfer by the fluid within the virtual wire crossing fully in parallel. The here utilized WMS consists of 16 transmitter and 16 receiver wires building a grid of 16 x 16 virtual crossing points with a wire pitch, and thus spatial resolution, of 4.412 mm. In total 188 of these crossing points are located inside the sensors inner diameter of 70.6 mm and thus used for data analysis.



**Figure 2.** Photograph of WMS for JOSSI facility with ceramic inlay (left) and ready installed (right)

## 2. Evaluation of the void fraction with the wire-mesh sensor

Before the evaluation could begin, the criteria for the various flow patterns had to be defined. This is particularly important, as in some cases the flow patterns are difficult to distinguish from one another and a subjective influence of the observer of the data cannot be completely excluded. For this purpose, Figure 3 was divided into several sections, which also capture the transitions between two flow patterns. The transition from one flow pattern to the next is gradual, so that the characteristics of the flow patterns often intermingle, making it difficult to draw a clear distinction. The defined characteristics of the sections are shown in Table 1.



**Figure 3.** Flow patterns for convective boiling in a horizontal tube [6]

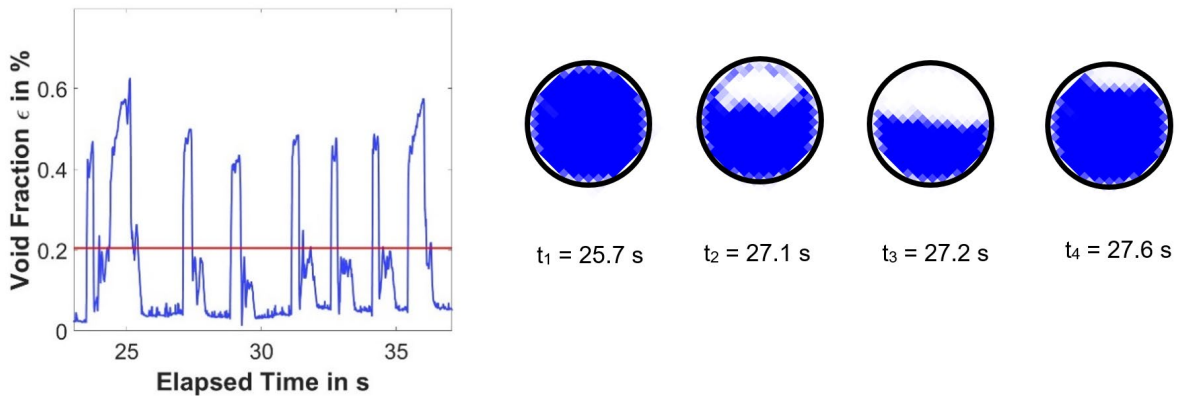
**Table 1.** Criteria for two-phase flow patterns

| Flow pattern                   | Max. liquid level | Max. void fraction | Characteristics                                                                                                                                                                                                                              |
|--------------------------------|-------------------|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. Liquid Phase                | 100%              | 0%                 | <ul style="list-style-type: none"> <li>Only liquid water</li> </ul>                                                                                                                                                                          |
| 2. Bubbly flow                 | High              | Low                | <ul style="list-style-type: none"> <li>Small gas bubbles</li> </ul>                                                                                                                                                                          |
| 3. Plug flow                   | High-Middle       | Low-Middle         | <ul style="list-style-type: none"> <li>Large gas bubbles</li> <li>No droplets within the gas phase</li> </ul>                                                                                                                                |
| 4. Transitional flow plug/slug | Middle            | Middle             | <ul style="list-style-type: none"> <li>Combines characteristics of plug and slug flows</li> </ul>                                                                                                                                            |
| 5. Slug flow                   | Middle-Low        | Middle-High        | <ul style="list-style-type: none"> <li>Periodic change in flow in vertical direction</li> <li>Upper pipe wall is frequently touched</li> <li>Droplets can detach from the liquid</li> <li>Smaller gas bubbles can follow the slug</li> </ul> |
| 6. Semi-slug flow              | Low               | High               | <ul style="list-style-type: none"> <li>Periodic change in flow in vertical direction</li> <li>Upper pipe wall is not frequently touched</li> </ul>                                                                                           |

For the visual evaluation, the profile of the void fraction over time was analyzed. In addition, the void fraction was observed over the cross-section at the absorber outlet. For the measurement campaign in October, mainly plug, slug and semi-slug patterns were observed, the characteristics of which will be discussed in more detail.

## 2.1 Plug flow

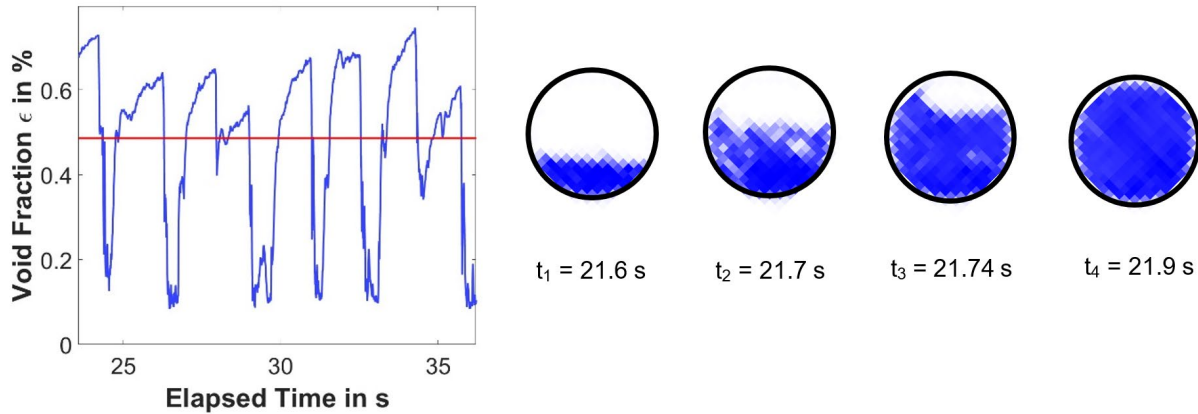
Figure 3 shows the typical behavior of a plug flow. Here, the vapor content rises sharply at intervals and then falls again shortly afterwards to a value close to zero. The flow structure is an alternating sequence of large bubble plugs in a completely liquid filled pipe. The plug flow differs from the slug flow by its lower maximum gas content and thus its overall higher liquid level. The slip velocity between the gas and liquid phase is low. On average, the operating point shown here has a mean void fraction of roughly 20%.



**Figure 4.**  $\epsilon$ - $t$  diagram and development of the void fraction over the cross section of the absorber outlet for a plug flow

The void fraction across the cross-section of the pipe is shown on the right side of Figure 4. The liquid is shown in blue and the vapor in white. At time  $t_1$ , there is still only liquid in the cross-section. After a few seconds, the grid sensor already measures vapor ( $t_2$ ), which migrates through the absorber tube in the form of an elongated bubble (plug), whereby the gas content initially increases ( $t_3$ ) until it drops again ( $t_4$ ) and pure liquid is present again.

## 2.2 Slug flow



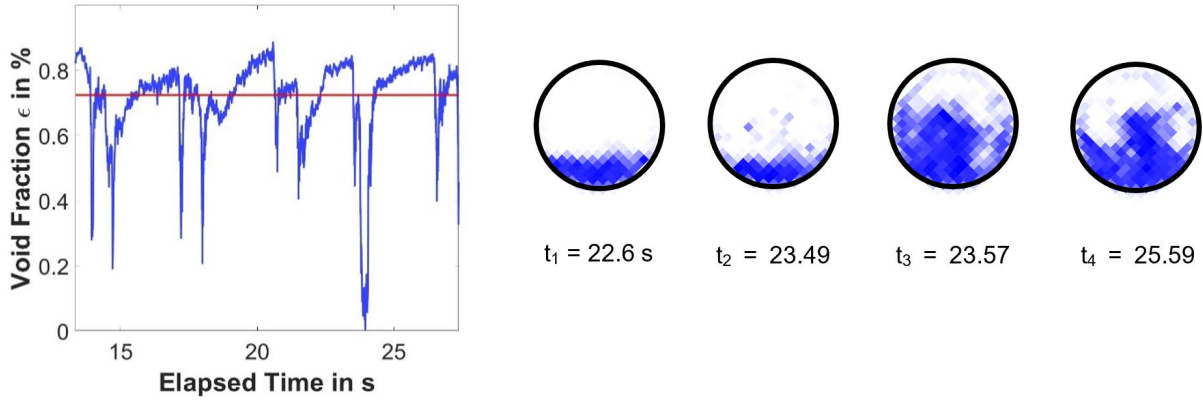
**Figure 5.**  $\epsilon$ - $t$  diagram and development of the void fraction over the cross section of the absorber outlet for a slug flow

If more heat is added, the vapor content increases further and the plug flow changes into a slug flow. The typical behavior of a slug flow is shown in Figure 5. The higher overall gas holdup with an average of 47% is clearly visible. Large pockets of steam are flowing with high velocities interrupted by short liquid slugs which are accelerated by the gas fraction over the mean liquid velocity. The liquid slugs contain smaller bubbles and thus the cross section has no longer 100% liquid fraction at any time.

The time characteristic of the void fraction over the cross-section differs slightly from that of the plug flow. In particular, the tail of the gas bubble shows a slightly different characteristic. At time  $t_1$ , the maximum gas content is present above the cross-section, which drops abruptly. The small gas bubbles that appear at time  $t_2$  can be clearly seen, which are in the tail of the slug and slowly decrease until mostly liquid fills the cross-section ( $t_4$ ) during a short time.

## 2.3 Semi-slug flow

If the gas content increases even further, the slug flow changes into a wave flow. At this point, it should be noted that two types of wave flow exist in the literature. A distinction is made between stratified wavy and annular wavy, the latter of which is meant here. In some literature, the transition between slug flow and annular wavy flow is referred to as semi-slug flow. This term was adopted in the project, as a clear distinction from the slug flow is advantageous for the assessment of favorable plant operation. This is because semi-slug flow is located directly at the beginning of the intermittent dry area and is therefore to be classified as an unfavorable flow pattern for system operation. In the intermittent dry area sufficient wetting of the upper inner pipe wall is no longer guaranteed. This can be observed very clearly in Figure 6. The average void fraction for the operating point shown is 72%.



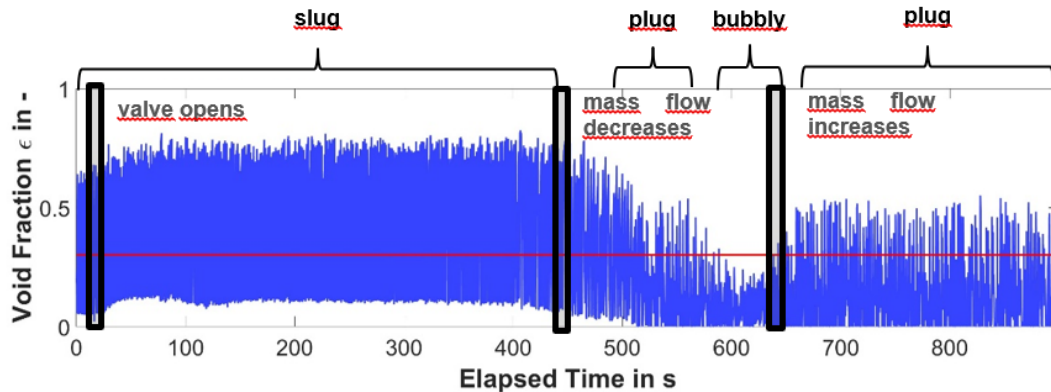
**Figure 6.**  $\epsilon$ - $t$  diagram and development of the void fraction over the cross section of the absorber outlet for a semi-slug flow

The semi-slug flow can also be distinguished from the slug flow by the less pronounced sudden drop in the void fraction. The slug often does not reach the upper inner wall of the pipe. The beginning of the separation of the gas phase from the upper inner pipe wall is also clearly visible. This can be observed during a slug/wave in the form of a crescent in the vapor phase distribution across the cross-section.

## 2.4 Transient operating conditions

In addition, the transient behavior of the flow pattern in the solar system had to be studied. For this purpose, it was investigated how the flow patterns change when clouds appear or steam is removed from the steam drum. As an example, the behavior of the flow pattern during steam extraction is shown in Figure 7. If steam is removed from the steam drum, the pressure in the drum and therefore also in the absorber tubes decreases suddenly. This initially causes more water to evaporate, which can be seen in an increase in the void fraction after 10 s when the valve is opened. The gas content in the flow initially remains at a stable level for several minutes before the recirculation mass flow begins to drop from 3.2 to ~2.35 kg/s at  $t \sim 440$  s, whereupon the flow pattern first changes to a plug flow and then to a bubbly flow. The mass flow then increases again until it reaches approximately 2.5 kg/s at time  $t \sim 630$  s. As the mass flow increases, the bubble flow changes back into a plug flow.

The occurrence of clouds and the resulting shading of the collectors was investigated by moving the collectors out of focus. While the mirrors remained defocused, no more heat was supplied to the absorber tubes. This also reduced the gas content of the flow, it was observed that the existing slug flow changed into a plug flow.

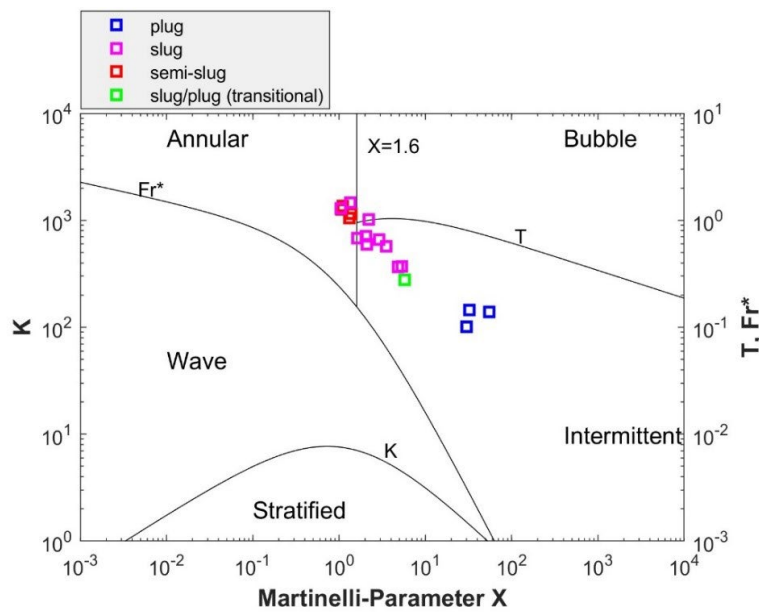


**Figure 7.** Void fraction over time for the case of steam extraction from the steam drum

### 3. Results from Flow Pattern Map

In the next step, the visually observed results of the flow patterns of 18 quasi-stationary operating points were compared with those from a flow map. For this purpose, the flow map according to Taitel and Dukler [7] was used, which can be used to read out the flow pattern depending on the Martinelli parameter and the Froude number.

It is not the void fraction but the vapor content of the flow that is required to determine the Martinelli number. In a two-phase flow, the differences in density between the liquid and vapor phases can lead to different flow velocities of the phases, also known as slip. This slip leads to the vapor phase running ahead of the liquid, which means that a simple conversion to the mass-related vapor content is usually no longer sufficient and the use of a slip model becomes necessary. The slip model according to Rouhani [8] was used for this work. The results of the quasi-stationary operating points are shown in Figure 8. For the comparison, the visually observed flow patterns were color-mapped and assigned in the legend.



**Figure 8.** Flow patterns of the quasi-stationary operating points in the flow map according to Taitel and Dukler [7]

When comparing the visually observed flow patterns with the results in the flow map, it is noticeable that the plug flow is found more to the right in the transition area, whereas the slug flow occurs closer to the boundary with the annular flow. The semi-slug flow is located directly at the transition to the annular flow. Although the observed flow patterns are all located in the intermittent area of the flow map, it is possible to make an initial estimate of the further pattern with the flow map. The semi-slug flow in particular is easy to read from the flow map due to its location near the boundary. Although some points marked as slug flow can also be found in this area, these already showed similarities to the semi-slug flow in terms of the course of the void fraction over time, meaning that they were already at the transition to the semi-slug flow. It can also be clearly seen that the transition between slug and plug flow is located between the corresponding flow patterns.

### 4. Conclusion and Outlook

During the measurement campaign, the flow patterns were mainly observed in the intermittent range. In particular, the semi-slug flow was identified as a possible critical flow pattern for system operation. There was good agreement between the results of the visual evaluation and

those from the flow map according to Taitel and Dukler. It can therefore be assumed that the flow map and a suitable slip model can be used to determine the type of flow that occurs. Although the flow map does not further differentiate the intermittent flow patterns from each other, the further differentiation between semi-slug, slug and plug flow according to the position in the intermittent area seems to be possible. However, in order to confirm this observation, more measurement data should be considered.

In August 2024, the second measurement campaign took place, in which an industrial version of the wire-mesh sensor with automated data analysis and flow pattern identification was installed, with which continuous measurements can be made. The data generated in this way can be used to verify the developed methodology in the future. In addition, the next step will be to expand the system monitoring based on the findings to date.

## **Data availability statement**

The data can be requested from the authors. A corresponding e-mail address is provided.

## **Underlying and related material**

There are no other associated materials.

## **Competing interests**

The authors declare no competing interests.

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## **Author contributions**

N. Konz contributed to the writing of the abstract, section 1, 2, 3 and the conclusion and outlook. E. Schleicher wrote subsection 1.2 and was part of the first measurement campaign. M. Mokhtar took part in the writing of 1.1, was part of the first measurement campaign and contributed with his technical know-how about the functioning of the system. M. Smeirah organized the communication with the Jordanian partners. D. Krüger coordinated the work between the project partners. All listed authors took part in the review of the paper.

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