Integrating National Research Agendas on Solar Heat for Industrial Processes

Project Deliverable 3.2:

D 3.2: – AVAILABLE SENSORS FOR MONITORING OF TWO-PHASE FLOW CONDITIONS		
WP	3 Technology and applications to medium temperature SHIP (150 °C to 400 °C)	
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1. Background

The main objective of the INSHIP project is "acknowledging both the potential contribution of Solar Thermal technologies towards the development of sustainable industrial production and the need of a coordinated effort tackling the technological challenges still faced by these technologies when applied in industry. INSHIP aims at the definition of a European Common Research and Innovation Agenda (ECRIA) engaging major European research institutes, with relevant and recognized activities on SHIP into an integrated structure." [1]

The Work Package 3 (WP3: Technology and applications to medium temperature SHIP (150ºC to 400ºC)) "covers the research topics related to the development of technological solutions aiming at the integration of medium temperature technologies in SHIP applications." [1]

Task 3.2 focuses on available sensors for monitoring two phase flow conditions inside solar powered steam pipes supplying industrial processes

The adoption of DSG concepts in solar fields, enabling a more cost-effective steam production in view of lower operation and investment costs (use of water as HTF instead of thermal oil, thus not requiring a thermal oil/water evaporator heat exchanger) as well as increased overall efficiency (related to the bypass to a thermal/oil/water heat exchanger) subtends that phase change occurs in the solar hydraulic loop.

The occurrence of phase change within a hydraulic circuit subjected to a potentially variable heat source, such as is the case of the solar collector absorber part of the circuit raises challenges from the perspective of control, in view of the potentially fast changing conditions of enthalpy, pressure, available power and heat transfer conditions. These changes might translate into different two-phase flow patterns inside the circuit, some of which might be harmful to the hydraulic circuit (e.g. stratified or dry-out flow patterns).

To the present, different strategies might be used to detect/inspect/foresee two-phase flow patterns inside hydraulic circuits, without any claims for comprehensiveness [1]:

- Visual methods: based on a transparent sight window section installed in the circuit, which might be then associated with video-based flow pattern identification techniques;
- Photon attenuation: use of X or Gamma rays through "one shot" or neutron scattering methods leads to high accuracy flow pattern detection but presents high costs and high installation and operation requirements;
- Wall pressure measurement: relates wall pressure fluctuations with different flow patterns. Enables the identification of some patterns but not annular/wavy stratified patterns;
- Electrical conductivity measurement: the use of a wired-mesh conductivity measurement on a tube section enables a fast visualization and quantification of two-phase flow patterns. This technique is though intrusive and high costly;

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- Refractive index measurement: through the use of a U-shaped optical fiber and hot-wire anemometry it is possible to detect void spaces within two-phase flows. This method is intrusive;
- Semi-empirical correlations: the use of semi-empirical correlations such as Kattan Thome and Favrat (KTF) [2] and their further developments [3, 4] enable a prediction of two-phase flow patterns as a function of mass flow rate and steam quality. Though, these correlations were produced for specific tube diameters and flow conditions, which might differ from the conditions found in real systems.

2. Terms and Definitions

Terms	**Description**
DSG	Direct Steam Generation
HTF	Heat Transfer Fluid
WMS	Wire-Mesh-Sensor
PE	Puerto Errado

3. DSG in solar thermal plants

Worldwide a substantial amount of heat is used to produce saturated or superheated steam for industrial processes and running turbines. Solar driven generation of process steam can be efficiently realized by concentrating systems. The incoming solar radiation is bundled and focused on an absorber in order to evaporate pressurized water. State of the art solar thermal DSG plants make use of line focusing types of collectors. One collector type potentially very suited for DSG applications is the Linear-Fresnel collector with its rigid, not tracked absorber tubes as it was already applied in several commercially running plants like PE 1, PE 2 from Novatec Solar (see Figure 1, left)or Industrial Solar's process steam producing plants at MTN, South Africa and RAM Pharma in Jordan (see Figure 1, right).

Figure 1: left: Novatec Solar's DSG power plant PE 2 [7] ; right: Industrial Solar Linear-Fresnel collector at RAM Pharma Industry in Jordan [4]

The Linear-Fresnel design with the fixed receiver tube and tracked linear mirrors (see Figure 2) is suited best for high pressure steam operation. However parabolic through are applied in DSG applications as well, due to their advantages in optical efficiency. Tough, parabolic troughs show a higher leakage risk because of their tracked absorber tubes and rotating joints , which connect the collector modules with each other and with the hydraulic loop of the solar field.

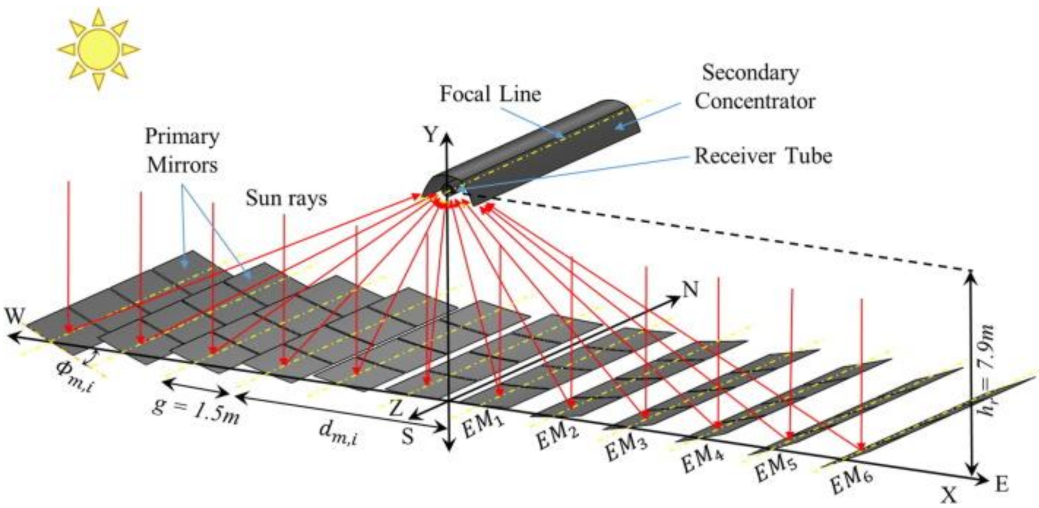

Figure 2: Schematic setup of Linear-Fresnel Collector

Plants based on direct steam generating Parabolic Trough collectors were for instance realized by Solarlite in Kanchanburi, Thailand (see Figure 3) and by Solitem at an aluminium surface specialist in Ennepetal, Germany (see Figure 4).

Figure 3: Solarlites Parabolic Trough collectors connected to the hydraulic loop of the 20,8 MWth solar field in Kanchanburi, Thailand [15]

Figure 4: Solitems 75 kWth Parabolic Trough plant at aluminium surface specialist Alanod in Ennepetal, Germany

DSG applied in concentrating solar facilities has advantages over plants with indirect evaporation using thermal oil as HTF, such as saving of heat exchangers and heat losses and the use of untoxic water as HTF and working fluid (compare Figure 5). However it possesses disadvantages such as the extensive requirements for withstanding the high system pressure and challenges in process control and operation stability.

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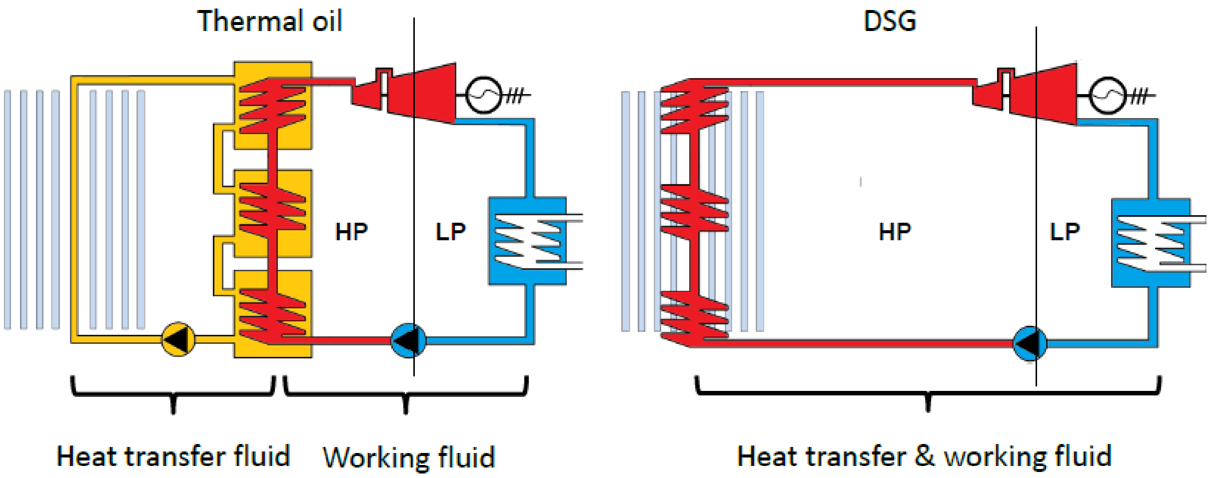

Figure 5: Heat exchange in plants with indirect steam production and in DSG Plants

The water/steam loop can be designed differently in order to meet the requirements of the specific facility and application. In general three basic methods of steam production can be applied in DSG solar fields (see Figure 6). For the recirculation approach a steam drum is needed to separate the produced saturated steam from the not evaporated water. The recirculated hot water is mixed with the feed water and pumped again into the collector loop. Depending on the application, the saturated steam can be superheated up to the set process temperature. For controlling the temperature of the absorber tube in the superheating collectors water can be injected at several points along the collector loop.

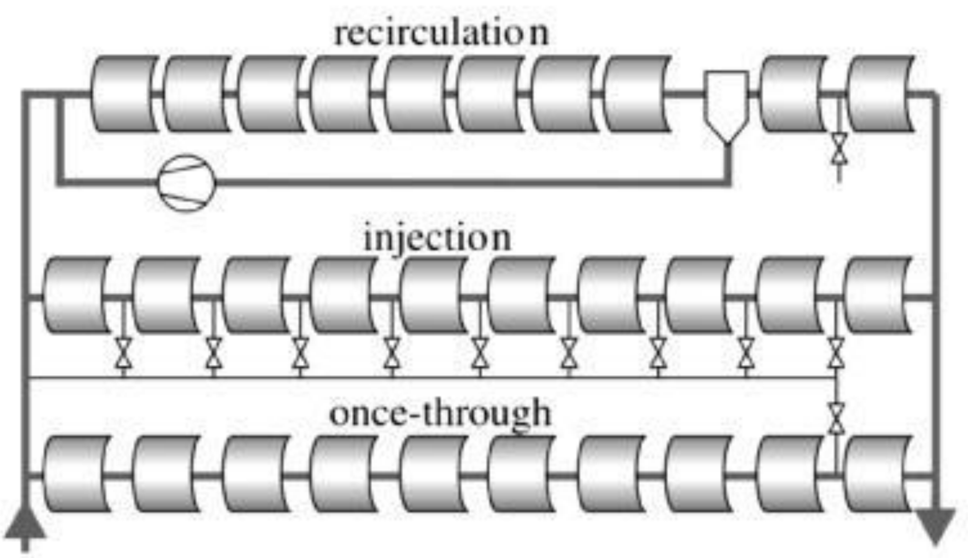

Figure 6: Solar DSG methods for steam production [6]

Within the once through concept, water is pumped into the collector and leaves it as saturated or superheated steam. In the DSG parabolic through plant built by Solarlite the steam is conditioned with a combination of recirculation with steam drum and subsequent superheating via injection cooling [15].

Running the solar thermal DSG plant on steady-state operation conditions is the overall aim of the plants control strategy. The control of the system faces disturbances by varying solar irradiation by the sun and different soiling rates of mirrors additionally to varying fluid inlet temperatures. Due to the variations consumption side the solar systems load can also change. To avoid dangerous and destructive conditions inside the solar loop and of course to reach the highest efficiency of the thermal system, a stable control is essential. For the implementation of a stable and efficient control regime, extensive knowledge on the different two phase flow conditions (see Figure 7) are required. While slug flow can cause vibrations and mechanical stress, a stratified flow can cause high temperature gradients in the cross section of the absorber pipe wall and hence also mechanical stress by non-uniform thermal expansion. Local dry outs caused by overheating can lead to severe damages of the absorber tube and other peripheral components. Therefore, the control strategy as well as the choice of operating conditions (i.e. the flow rate)is based on expected two-phase flow patterns. Without the knowledge of the actual two phase conditions, they have to be determined by simulations based on physical models. As the determination of the conditions is complex and goes along with many assumptions, the detection of the water steam distribution inside the absorber tube is highly desirable and leads to an optimized and secured control regime. [4]

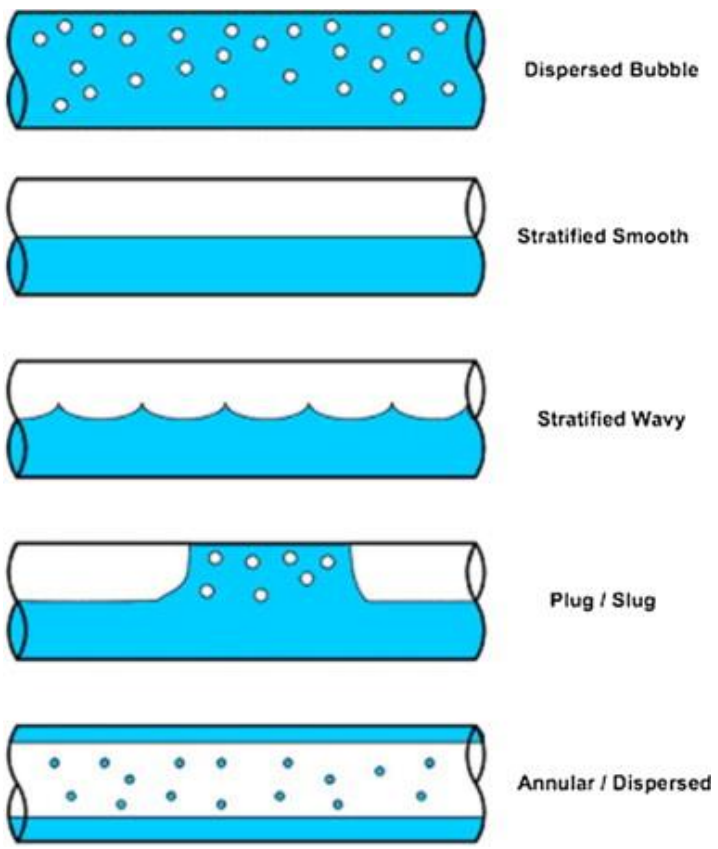

Figure 7: Schematic depiction of two-phase flow patterns in horizontal pipes [13]

4. Available sensors for analyzing two phase flow conditions

4.1. Visual method by strobe and camera

Visual methods can be used to observe different flow patterns inside a tube. For this approach a transparent sight tube with the same inner diameter as the process piping has to be installed. A possible setup for flow pattern observation is depicted in Figure 8. A strobe emits pulsed light in order to pass the depicted diffuser and the sight tube. The combination of strobe and diffuser is used to stop the appearance of motion inside the tube in order to make the desired flow pattern visible via the camera.

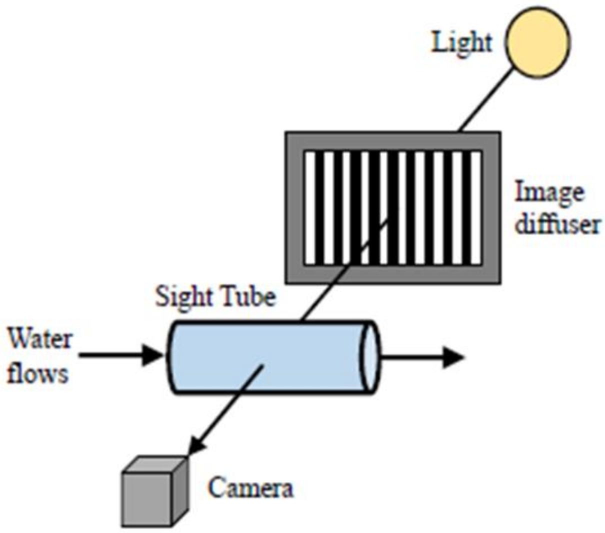

Figure 8: Possible setup for visual flow pattern detection [1]

There are approaches with CCD and normal cameras working with a frame rate according to the frequency of the strobe. In Figure 9 some results of the described procedure are given. Some typical flow patterns have been discovered with this technique in the field of refrigerants in small pipes by Jassim et al.[14]. Jassim et al. were using a modified webcam in combination with image detection for an automatically interpretation of the received image of the pipe section. Antoine Frein used the approach performed by Jassim to analyze multiphase steam/water flows at different parameters [1] .

Worldwide many approaches using a camera for the detection of multiphase flow behavior, but none of them was developed up to a compact commercially available working sensor unit that can be integrated (including the sight tube) into solar driven steam networks.

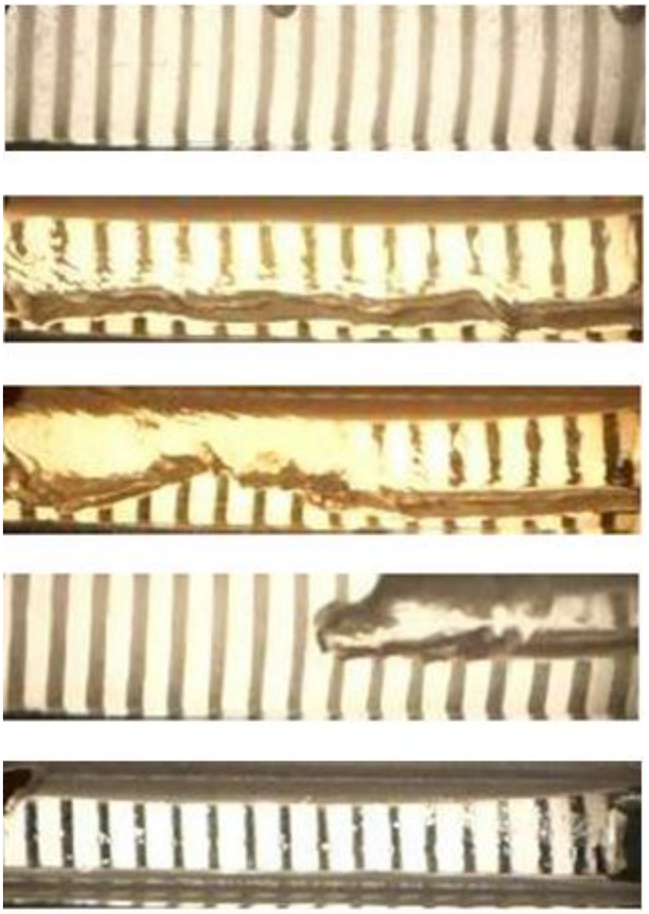

Figure 9: Camera observed flow patterns (complete fluid; stratified; wavy stratified; elongated bubble; annular) [1]

4.2. Sensor based on Photon Attenuation

Detection of void fraction and visualization of flow patterns can be realized by photon attenuation methods. With a source of photons (X-Ray, Gamma-Ray, light, etc.),which are penetrating the steam pipe, it is theoretically possible to interpret the measured attenuation by computer tomography as locally resolved water and steam distribution. A prototype sensor from the Helmholtz Zentrum Dresden Rossendorf (HZDR) runs multiphase flow analyses by using an optical approach. The sensor is able to visualize the actual void fraction in a cross section of a pipe at high frequency. The generated frames can be used to visualize a pseudo 3D model which shows the distribution of water and gas over a given time period. Beneath the attenuation of the photons when penetrating water/steam, the refractive index of the occurring phases inside the steam pipe, and the resulting deflection of the photon is also considered when visualizing the void fraction.

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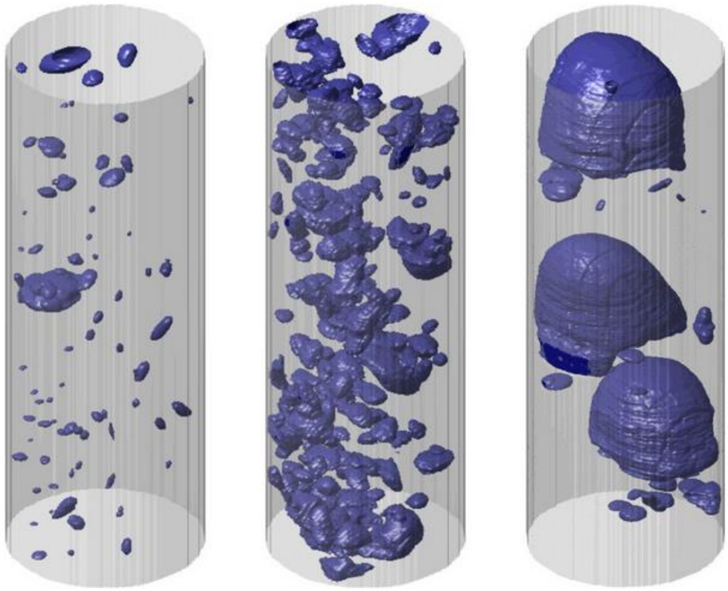

Figure 10: Pseudo 3D model of water-gas multiphase flow [5]

On the interior circumference in a cross section of a pipe light receivers and emitters are installed (see Figure 11). When one of the emitters sends out light, all the receivers detect the incoming intensity of light, which is influenced by the two occurring phases inside the pipe. Due to the amount of emitters and receivers and the high operation frequency, the distribution of water and gas can be calculated. As the prototype was built to measure bubbles inside liquid flows with a void fraction up to 10% gas, the sensor is at current configuration not suitable for analyzing steam systems 0.

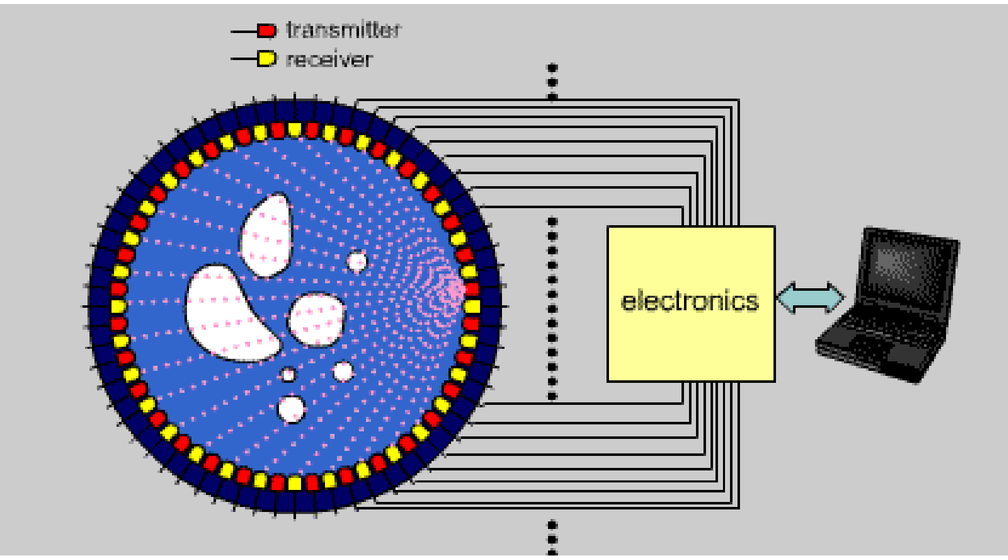

Figure 11: Schematic illustration of the sensors principle [5]

4.3. Sensor based on conductivity

A way to achieve a fundamental understanding of the two-phase flow conditions inside steam lines is to observe the flow with a wire-mesh sensor, such as the one developed by the Helmholtz Zentrum Dresden Rossendorf (HZDR). The sensor is located between two flanges in the cross section of a pipe and delivers high definition data of the distribution of steam and water (see Figure 12). This information can be used to validate expected flow pattern profiles (see Figure 7). Furthermore, the average steam mass fraction in the cross section can be determined based on the set of measurement points . The flow patterns inside the tube, discovered by the WMS, deliver essential information on the actual heat transfer characteristics within the tube.

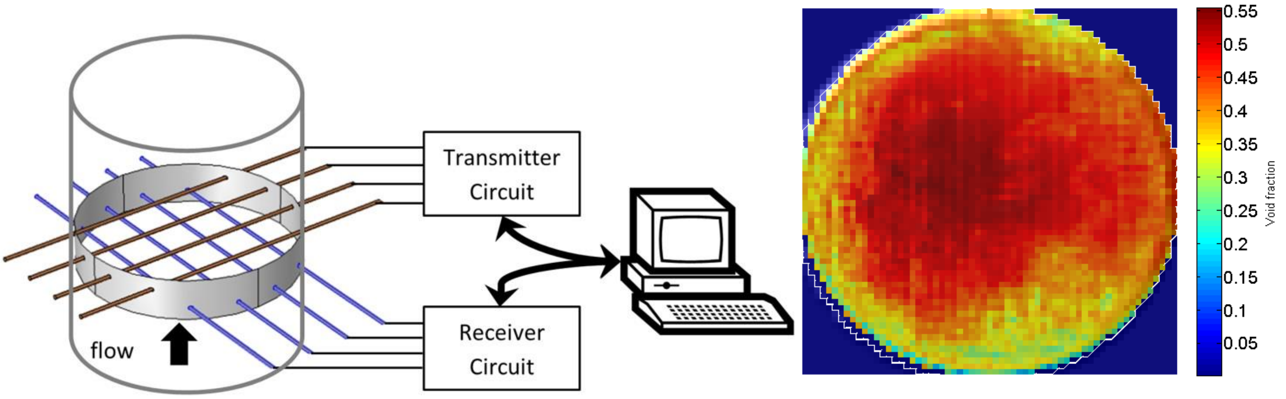

Figure 12: left: Principle of WMS; right: visualization of WMS measured void fraction at a pipe cross section [5]

The wire-mesh sensor, developed by the HZDR, is based on a mesh arrangement of the measuring points. It consists of two mesh layers that are installed normal to the direction of flow with a small gap between the layers. On each layer, wire electrodes are arranged in parallel and the grids are perpendicular to each other. This gives a grid of electrodes in the axial view, which covers the entire cross section (see Figure 12, left). The transmitter electrodes are sequentially activated while all receiver electrodes are parallel sampled, in such a way that the electrical conductivity of the fluid is evaluated in each crossing point. The measured current depends on the local conductivity of the fluid at the virtual crossing point. In case of water, a current is measured at a crossing point between transmitter and receiver electrode due to the electrical conductivity of water. However, an electric current cannot be measured when a steam bubble encloses a crossing point. The arising receiver currents are converted to a voltage and subsequently to a digital signal, which is transferred to the data logger. The instantaneous void fraction is determined for each crossing point. All local instantaneous void fractions in the cross section of the pipe are collected in a frame. The wire mesh sensor achieves a maximum temporal resolution of 10,000 frames per second. [9]

4.4. Prowirl F 200 from Endress und Hauser

Another available Sensor presented in this report, which gives us information on void fraction is the Prowirl F200 from Endress and Hausser. It is a vortex flowmeter with an additional wet steam detection. In Figure 13 the principles of vortex flow measurement are depicted. The flow in the pipe hits the element and vortexes are generated. The hinged paddle (in Figure 13 called "Sensor") is influenced by the vortexes coming alternating from left and right. The signal from the detected movement of the paddle in combination with measured pressure and temperature can be interpreted as a mass flow. The paddle can also be influenced by the liquid flow inside the steam pipe. In case of a stratified flow pattern the paddles movement is also influenced by water flow running at the bottom of the pipe and generates a second signal. This influence can be detected as well in order to analyse the amount of water running through the pipe. The range of measurable void fraction is from 80-100%. The sensor can be integrated into steam processes with a temperature up to 185 °C and a maximum pressure of 11 bar. [11]

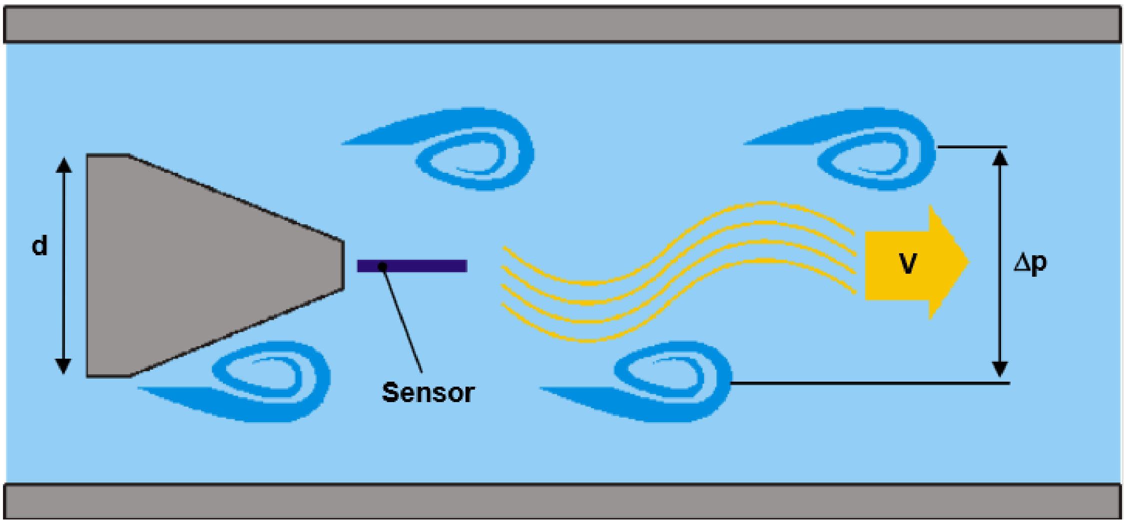

Figure 13: Vortex flow measurement principles

5. Conclusion

There is no doubt that a proper sensor for detecting void fraction and/or flow patterns inside a steam tube of a transient process is a great opportunity to improve the control regime of a solar thermal plant based on DSG in order to increase the operation time running in steady-state mode. Due to the fact that multiphase flow occurs in so many applications (energy sector, food and beverage industry, oil industry, cooling technology and many others) many research groups all over the world developed sensor concepts to find solutions for detecting void fraction and get information about the upcoming flow patterns. But, lots of those concepts are limited to specific applications with specific boundary conditions, such as process pressure and temperature, void fraction, mass flow, pipe diameter and pipe materials. With regard to the task of finding available sensors for monitoring two-phase flow conditions in SHIP applications, I can say that there is almost nothing available at present. The best suited sensor for SHIP application will be WMS sensor from HZDR. This sensor can operate in a wide range of pressure/temperature/void fraction that suits well to SHIP applications. Even if the sensor may be best suited to SHIP, it is a sensitive sensor with complex read-out electronics infrastructure, which is not easy to install. Nevertheless the sensor was already successfully installed in different DSG solar plants to enhance the process knowledge of the plant's operators. Currently the sensor is commercially available at HZDR Innovation[12] . As described in 4.4 the Prowirl F200 is commercially available at Endress and Hauser. Due to the mentioned temperature and pressure limitations the sensor will be well suited for many ship *applications and can support the process with the measured void fraction. Unfortunately it is not able to give information on flow patterns. As there are currently not many information on the sensors principles it is hard to say how the sensor can improve SHIP applications operation.*

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