

Water Circulation Calculation for Concentrated Solar Thermal Plants

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Abstract

To ensure functionality and ultimately financial success of a Concentrated Solar Power (CSP) plant guaranteeing a safe and reliable working fluid circulation is crucial. This applies to line as well as point focusing systems whereby both face different challenges. Obviously, the working fluid used affects the system layout as thermal oil, molten salts or water behave differently when being heated up.

This papering investigates ways to optimise the working fluid circulation in different CSP systems focusing on Direct Steam Generation (DSG). However other working media such as thermal oil, molten salts and air will be discussed as well. A number of lessons can be learnt from traditional boiler design using well established design tools and procedures to reduce design cost and risk.

Keywords: Direct Steam Generation, Water Circulation, Two-Phase Flow, Fluid Distribution, Molten Salt, Thermal Oil

1. Introduction

Realising reliable and safe Direct Steam Generation (DSG) in Concentrated Solar Power (CSP) plants is a technical challenge worth taking on as DSG has a number of inherent benefits over Indirect Steam Generation. One of the benefits is that water is a safe and non-toxic fluid, hence conditioning and disposal is simple. Thermal oils, currently being the predominant heat transfer fluid, contain a number of chemicals, which raise environmental issues in case of absorber tube damage/spilling and final disposal. In addition they incur a higher specific investment per liter.

The main benefit of DSG is the expected Levelised Cost of Electricity (LCOE) reduction and improved plant efficiency. Having an intermediate fluid, such as thermal oil, requires the use of capital intensive heat exchangers which inherently incur efficiency losses.

On the other hand DSG does require a high technical know-how to properly design the steam generation system. While the pressure of thermal oil in absorber tubes does not exceed 22bar, pressure levels of 100bar and higher can be expected in DSG systems. The operation of DSG plants is more complex too as two-phase flow conditions have to be avoided. Fluctuating steam conditions, oscillation etc are additional issues to be considered carefully by the plant designers/operators.

However, these issues are not completely new to the steam generation industry. Effects of sudden load changes, heat flux variations, horizontally and vertically arranged heating surfaces are well studied with a variety of proven solutions in commercial operation. ERK Eckrohrkessel GmbH (ERK) and its numerous licensees are working for more than 60 years in the boiler industry. The design experience of several thousand natural and forced circulation boilers/heaters as well as permanent R&D allow the transferability of traditional boiler design tools to line as well as point focusing CSP systems at low risk. The preferred choice for line focusing systems is forced water circulation while point focusing systems can be designed in natural circulation.

2. Direct Steam Generation

Basically, all conventional power plants generating electricity use water-steam as the working fluid with the exception of a few small units using Organic Rankine Cycles. Currently, the most mature CSP technology in operation is Parabolic Trough with indirect steam generation. These plants operate reliably but their drawback is the use of thermal oils that cannot cope with temperatures above 400°C for extended periods. Hence steam temperatures are limited to < 400°C with all negative effects associated on the plant efficiency. Recently, DSG was introduced in Parabolic Trough Plants which promises higher plant efficiencies and lower LCOE.

Next to Parabolic Trough other CSP technologies such as Fresnel, Tower and Dish systems use, amongst other working fluids, DSG to generate power.

2.1. Design considerations for traditional boiler systems

The design of boiler systems is an engineering field with experience accumulated over many decades. Understanding of the technical principles as well as software accuracy has improved significantly allowing the design of more flexible and reliable boiler/heater systems. However, many companies active in the boiler business did not engage with the solar industry and vice versa, which lead to design failures and longer development times than necessary. Nowadays both industries recognise that they can learn from each other and engage more closely.

Designing the cooling system is vital for any boiler no matter if the energy source is the sun, biomass, gas or coal. Solar boilers present a few additional challenges like quick load changes or particularly long horizontally arranged heating surfaces. However, even these issues were addressed in a few traditional boilers for special applications. Some units operating realise load change capabilities of 20%/minute (see Figure 1) while others use horizontally arranged heating surfaces (heating surfaces not as long as in line focusing systems though). These systems operate either with natural or forced circulation.

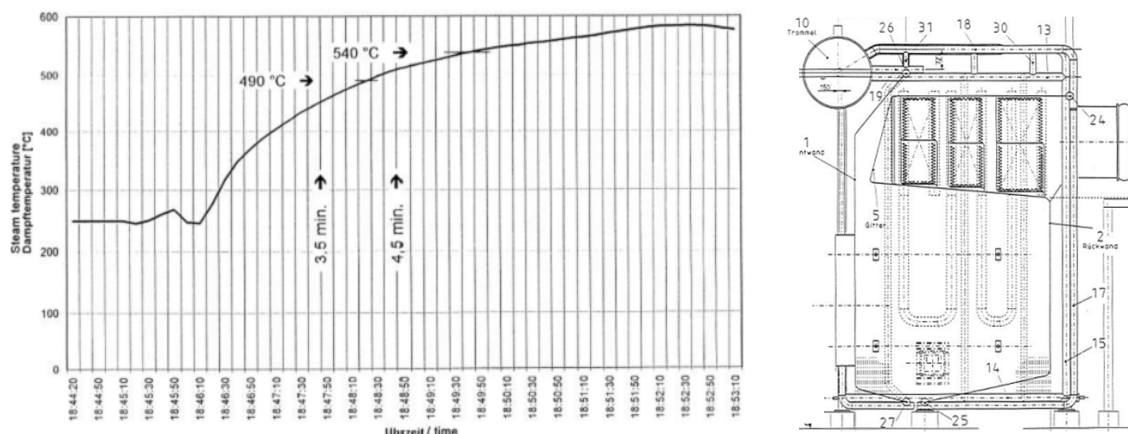


Figure 1: Quick start-up boiler (130t/h, 540°C and 36bar) in Cottbus, Germany (right) with steam temperature/time graph (left)

2.2. Line Focusing Systems

Line Focusing Systems (LFS) such as Parabolic Troughs or Fresnel plants with their long horizontally arranged absorber tubes pose a particular challenge when using water-steam as working fluid as flow stratification can occur quickly during two-phase flow (see Figure 2). The evaporators are most threatened followed by boiling in the economiser/preheating section.

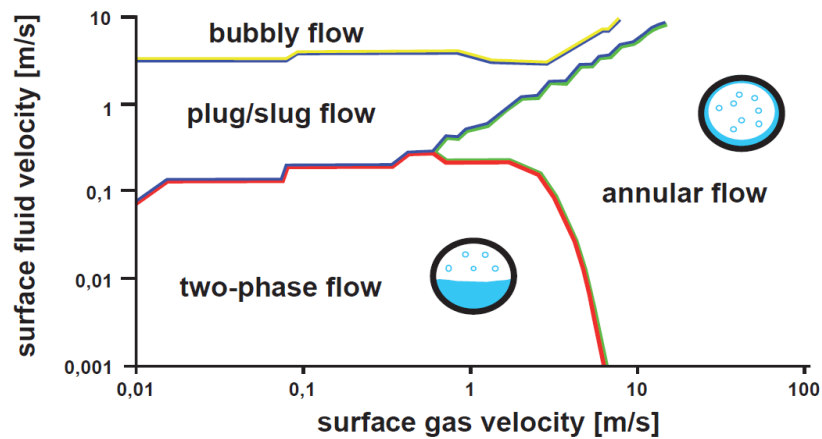


Figure 2: Types of two-phase flow in horizontally arranged absorber tubes [1]

Out of natural, forced and once-through water circulation only forced and once-through is suitable for line focusing solar boiler (see Figure 2). Natural circulation is not an option because the driving force is insufficient. However, it is a suitable option for point focusing systems (see chapter 2.3).

The once-through process is a simple design, as preheating, evaporation and superheating happens in the same absorber tube (see Figure 2). For that reason the energy requirement in the plant is quite low. However, it is not the preferred operating option for LFS. Firstly, the absorber tubes have to cope with strong heat loads in the water to steam transition area. This poses a safety risk which is very complicated to solve in a solar field exposed to drastic heat flux changes due to e.g. cloud cover. Secondly, there is no possibility to control the mass flow of the HTF after entering the absorber tube. Hence, all plant components must be able to handle the varying mass flows.

One possibility to deal with problems of once-through systems offers the Injection process (see Figure 2). Spray attenuation at the end of each solar field section is an option to control the type of flow throughout the complete solar field. The sprays added throughout the absorber tubes increase the mass flow but also cause energy losses. The downside of the enhanced flow control through dynamic spray attenuation is the higher capital requirement for the additional equipment required.

Another stable solution for the DSG is provided by the recirculation-process (see Figure 2). This concept has thousands of fossil fuel fired boiler systems, e.g. La Mont design, operating at capacities similar to current and future solar steam generators. In contrast to the aforementioned concepts the preheating and superheating section is separated from the evaporation section by a steam drum. The economiser section is supplied with more water than it could possibly evaporate to ensure excellent cooling of the absorber tubes. Saturated steam from the evaporators is supplied to the superheater section.

Superheated steam temperatures in excess of 500°C are possible with all three concepts but the recirculation system is preferred as it allows the safest operation of the solar steam generator.

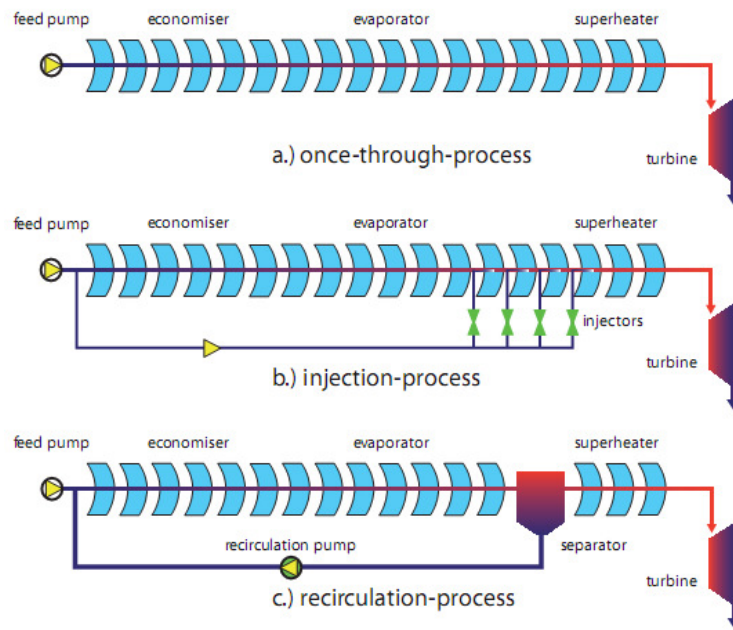


Figure 2: Once-through steam generator (top) with and without spray attenuation (top& middle) and forced circulation solar steam generator (bottom) [2]

The preferred flows in an absorber tube are bubbly, plug, slug and annular flow as they ensure cooling of the complete tube wall (see figure 3). The volume and velocity of the circulating fluid inside the absorber tube should not fall below a heat load dependent threshold to avoid two-phase flow/flow stratification. Flow stratification can quickly lead to significant thermal stresses in the absorber tubes as the mirror facing side of the tube is cooled by water whereby the top part of the tube is only cooled by steam (see Figure 3). This results in shortened absorber tube lifetimes caused by fatigue cracks and corrosion scenarios on the boundaries of water and steam.

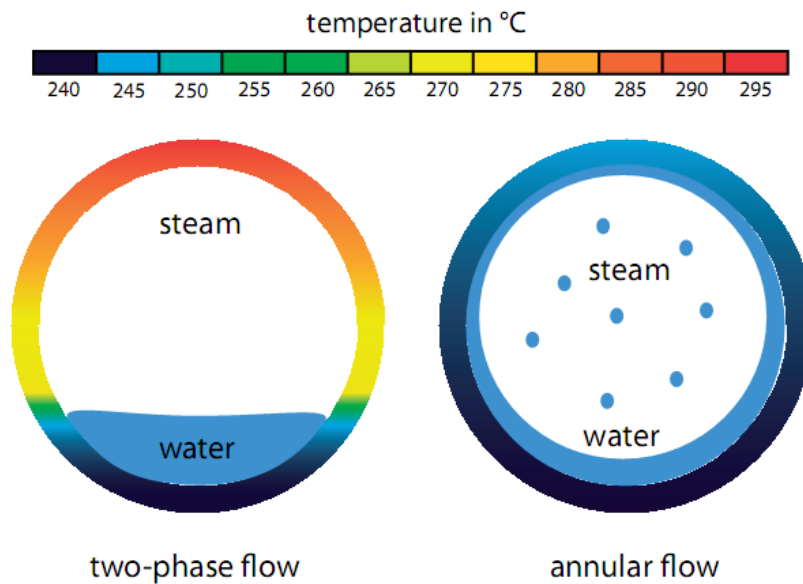


Figure 3: Tube wall temperature differences for two-phase flow and annular flow [3]

2.3. Point Focusing Systems

The design of receivers for Point Focusing Systems (PFS), such as solar towers and dishes, is more closely related to conventional boiler designs than line focusing systems. Heat fluxes are significantly higher than in line focusing systems and hence closer to values seen in gas, oil, coal or biomass fired boilers.

Different to line focusing systems receivers for solar towers can operate with natural and forced circulation. Natural circulation reduces the operational costs as there is no need for a circulation pump. It is applicable when using vertically arranged heating surfaces as the driving force is sufficiently high. Horizontally arranged absorber tubes require forced circulation as in line focusing systems.

As in forced circulation systems the water-steam mixture in the absorber tubes of a natural circulation system is separated in a drum. Subsequently, the separated water and condensate are resupplied to the heating surfaces. The saturated steam leaving the drum enters the superheater section for further temperature increase to the desired level, typically 400-600°C.

To shorten start-up times thermal stress of the material has to be minimized. To achieve this the wall thickness of the boiler drum should be as low as possible without jeopardizing safety. Few penetrations of the drum and pipes to pre-separate the steam outside the drum wall are favorable to achieve this.

The example presented in Figure 4 is a comparison of a forced (left) and natural circulation (right) receiver for a solar tower. The steam parameters are 40t/h at 100bar and 500°C. In the forced circulation design all heating surfaces are arranged horizontally. The natural circulation design on the other hand has horizontally arranged tubes only in the superheater and economiser section but vertically arranged tubes in the evaporator section. Both receivers can cope with varying heat fluxes across the heating surfaces.

The feedwater is fed into the bottom part of the economiser and exits the tube bundle close to saturation temperature. After being fed to the drum the heated water enters the evaporator section where it is further heated and partly evaporated. Subsequently, the water steam mixture returns to the drum is separated into water and steam, whereby the water returns to the evaporator and the saturated steam enters the superheater section.

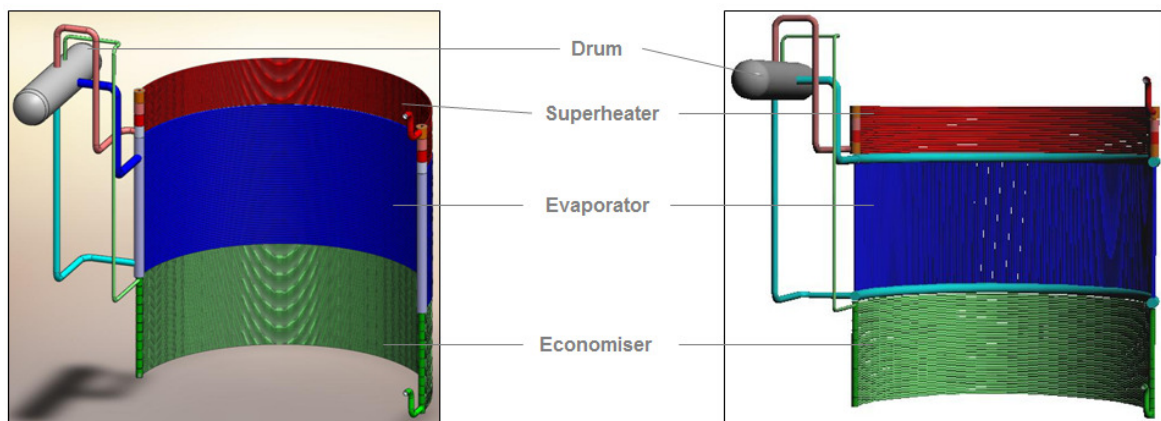


Figure 4: Design of a forced (left) and natural (right) circulation receiver for a solar tower with DSG

3. Additional Working Media

Other working media do not have the two-phase flow problem water-steam has. Hence they are favorably looked at for indirect steam generation.

Thermal oils are predominantly used in Parabolic Trough plants but it starts to degrade quickly at temperatures above 400°C, thus limiting steam temperature and efficiency. Molten Salts can reach temperatures above 550°C while allowing the simple integration of thermal storage in the primary cycle. Air possesses some very promising features as it is available in arid areas, easy to heat up and usable to operate a

highly efficient hot air combined cycle plant. Reactors combining e.g. natural gas with steam or carbon dioxide are very promising too but such technologies are still very much in its infancy.

3.1. Differences to DSG

Depending on the alternative working fluid to DSG, different benefits arise. At identical temperatures a water-steam system has a higher enthalpy than thermal oil (see Figure 5) or other working fluids. Obviously, this is an important benefit.

Temperature levels achievable for DSG and molten salts do not vary much (around 550°C) with air being able to realise the highest temperatures of all (>800°C). The disadvantage of air is the lower heat transfer rate which causes the receiver to be larger than for water-steam or molten salts.

Considering the operational pressure thermal oil, molten salts and air have benefits over DSG as tube wall thickness requirements are lower, thermal stresses lower and start-up times shorter.

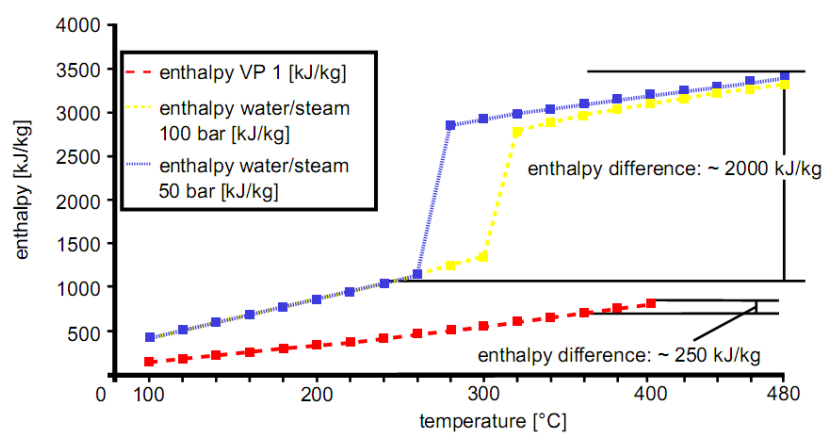


Figure 5: Enthalpy of water-steam and VP1 heat transfer fluid [4]

3.2. Molten Salts

Molten salts offer the simple integration of thermal storage into the primary cycle, while being able to generate high temperature steam and operating the primary cycle at low pressure. Two-phase flow issues do not exist, thus simplifying design and operation of the plants.

For solar tower systems molten salts are very applicable as the tower can be easily drained during the night/extended cloud cover or kept warm with minimal trace heating. Currently, the Gemasolar project in Spain is the most advanced plant using molten salts in the world.

For parabolic troughs the use of molten salts is likely to cause more problems as the solidification inside the long network of absorber tubes has to be avoided. This requires extensive and energy intensive trace heating. On the other hand the high steam temperature potential can justify the use of the operational intensive molten salts. In the end the economics determine the project viability. Currently, the Archimede project in Sicily is the only commercial size Parabolic Trough plant using molten salts.

3.3. Thermal Oil

Parabolic trough plants using thermal oil have a long history and had the chance to realise significant learning curve benefits. Currently, Parabolic Trough plants with thermal oil are the most bankable technology but with improving maturity of DSG, molten salts, air and syngas systems their future is uncertain as they suffer from lower efficiencies.

Thermal oil does not suffer from two-phase flow problems and solar heaters are easier to design and operate than a comparable water-steam system. Only Parabolic Trough plants use thermal oil as the primary working fluid and the best known references plants are the Solar Energy Generation Systems in the US and the Andasol plants in Spain.

3.4. Air

Except for Dish systems driving Stirling engines air systems for high temperature steam generation or gas turbine operation are still in its infancy. Obviously, the benefit of air being available in the most arid areas of the world and the high efficiency potential in conjunction with supercritical steam generation or gas/hot air turbine operation are promising. Until now air has been used in Dish and Solar Tower projects only.

Different to DSG air does not require high operational pressures and has no two-phase flow related problems. Problems lie in the lower heat transfer rates, which result in larger and hence more capital intensive receivers. Material availability and the high temperatures to be handled pose problems in terms of long-term survivability but ongoing research will solve these issues in the medium term.

3.5. Synthesis Gas Reactors

Syngas generation in form of methane reforming and other approaches is certainly promising for the future but far from commercial operation at the moment. The efficiency potential and the ability to use solar thermal energy for other products than electricity and heat is unique to this technical approach and will attract further research.

The reactor design is a complex task with additional issues to be taken into account to DSG, e.g. reagent distribution and temperature profiling. Currently, operational pressures are lower than in a DSG system but the complex chemical reactions require a very precise design and operation of larger plants in the future.

4. System optimisation

Currently, a number of options to optimise the efficiency/operatability of CSP plants, such as steam temperature increase or natural water circulation, were already mentioned earlier in this paper or are widely discussed in the scientific/industry community. Two technologies not used in the CSP field yet are the patented “ip tube[®]” (see figure 6) and “ip tube[®]+micro” technology (see Figure 7).

ip tubes can be manufactured from any material as long as the ductility properties are suitable. Dimple shape, size, spacing and depth are well studied for a wide variety of working fluids and have to be adapted to each application to realise the ideal outcome in terms of heat transfer, pressure drop, fouling and working fluid mixing. The enhanced mixing inside the tubes equilibrates temperatures, thus avoiding hot spots. This is particularly beneficial for thermal oil applications as they degrade quickly at temperatures above 400°C. It is also expected that the structure reduces two-phase flow forming due to permanent mixing. This would be an important feature for all DSG systems.

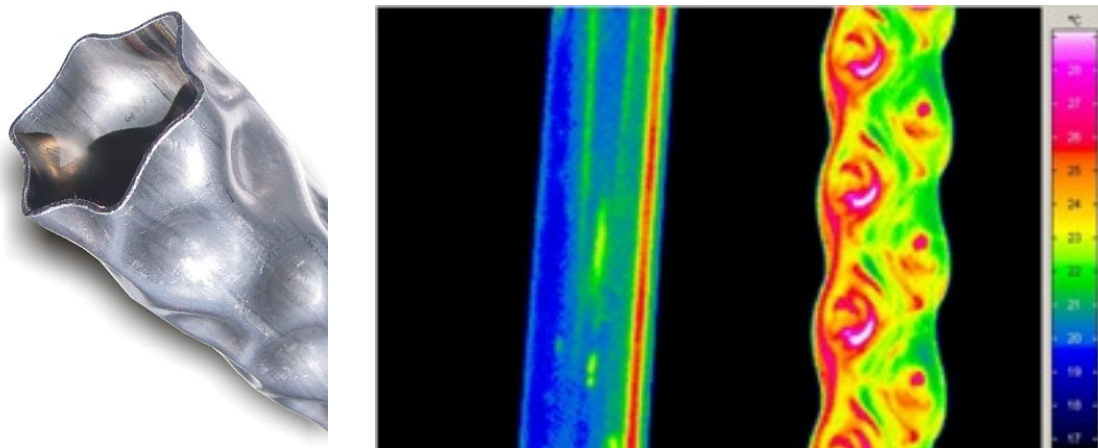


Figure 6: ip tube[®] Example (left) and ip tube[®]/plain tube heat transfer comparison (right)

In addition to ip tube[®] the ip tube[®]+micro technology has beneficial absorptivity properties as it traps incoming light inside the micro structure on the tube surface.

Currently, tests with several ip tube[®] and ip tube[®]+micro examples are carried out specifically for solar applications. First results for air receivers show that at a Reynolds number of 20,000 the Nusselt number is twice as high (100) in comparison to plain tubes.

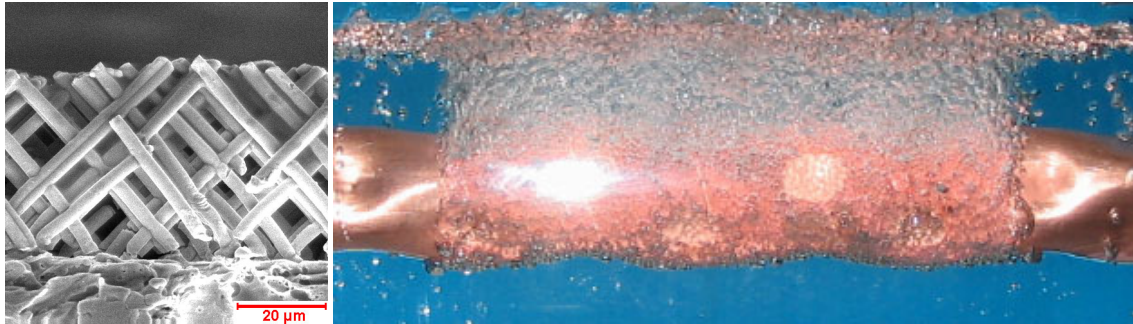


Figure 7: ip tube[®]+micro structure (left) and enhanced boiling tests (right)

5. Conclusion

In conclusion the use of DSG for future Concentrated Solar Power plants is a very interesting option to raise plant efficiency. However, the design of such steam generators requires a lot of experience, which is available in the traditional boiler industry. Transferring this knowledge through cooperation will lead to shorter design times for DSG plants with enhanced operational capabilities. The trial-and-error approach sometimes used in the past is a) very costly and b) not acceptable in today's financial circumstances anymore.

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