Partial stagnation in direct-flow vacuum tube collectors: Conditions for occurrence, risks and consequences

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Abstract

Partial stagnation means that the heat transfer fluid evaporates inside a solar thermal collector field although the pump is operating and the collector field outlet temperature is significantly below the evaporation temperature. This happens at a pronounced non-uniform temperature distribution in combination with a low mass flow rate and/or a high temperature level. ISFH investigated the conditions for the appearance of partial stagnation at a direct-flow vacuum tube collector group. Experiments were conducted to identify further criteria that promote partial stagnation: a low system pressure, an unequal flow distribution and a high gas content of the fluid. Measurements show no efficiency reduction during partial stagnation at a horizontal collector slope. With several collector groups connected in parallel, partial stagnation of high intensity could pass into full stagnation in some of the collector groups. This would lead to a significant efficiency reduction of the collector field.

However, partial stagnation leads to an unstable operation and a high load of the collector fluid and should therefore be avoided in any case. Possible measures are a more equal flow distribution obtained by the collector and collector field design as well as the removal of air and/or solid particles. In addition the system pressure level may be increased or the gas content solved in the fluid may be reduced.

1. Introduction

Partial stagnation is the evaporation of heat transfer fluid inside a solar thermal collector in operation, i.e. when, at the same time, the pump is running and heat is being removed. Thus, partial stagnation is clearly differentiated from full stagnation in which forced circulation of the fluid inside the solar thermal system does not take place. Partial stagnation occurs in direct-flow solar thermal collectors if the fluid temperature exceeds the boiling point in one or more locations within the collector field. For this to happen, the collector must be operated at a high temperature level with an irregular temperature distribution. Such temperature distribution may be caused by unequal flow distributions or the collector design itself. In addition, a low total mass flow rate, a low system pressure and/or a high irradiance level must be present to exceed the boiling point. While full stagnation is a projected operation condition, already investigated in detail within several projects [1], [2], partial stagnation always occurs as an unplanned effect. There is a lack of research about the processes at partial stagnation.

In the framework of a research project[1] ISFH investigated partial stagnation on a direct-flow coaxial vacuum-tube collector group with the aim of detecting the conditions required to cause partial stagnation and determining the effect on collector performance.

2. Experimental Setup

The ISFH conducted numerous outdoor measurements on a collector group consisting of two modules with a total number of 60 tubes connected in parallel at a horizontal collector slope (Fig. 1). For a detailed analysis, temperature sensors were installed at each outlet of the 60 tubes.

Fig. 1. Experimental setup at ISFH test roof 3.

With a high temperature thermostatic testing device operated with a common water-glycol mixture, it was possible to vary the inlet temperature and the mass flow of the collector group within a wide range. The mass flow rate was adjusted manually or controlled with a bypass parallel to the collector group. Thus partial stagnation of varying intensity and duration could be induced. Moreover, further variations were investigated such as collector hydraulic (one-sided or reverse-return connection), system pressure and dissolved gas content.

3. Results

Through the reduction of mass flow at a constant collector inlet temperature of 80°C, the minimum mass flow was identified, below which partial stagnation occurs in one of the tubes. Fig. 2 shows the method by the way of an example temperature pattern.

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1 The project with the title „Analysis of the low efficiency of a collector array for a solar assisted cooling system“ was supported by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU), project code: 0329283A.

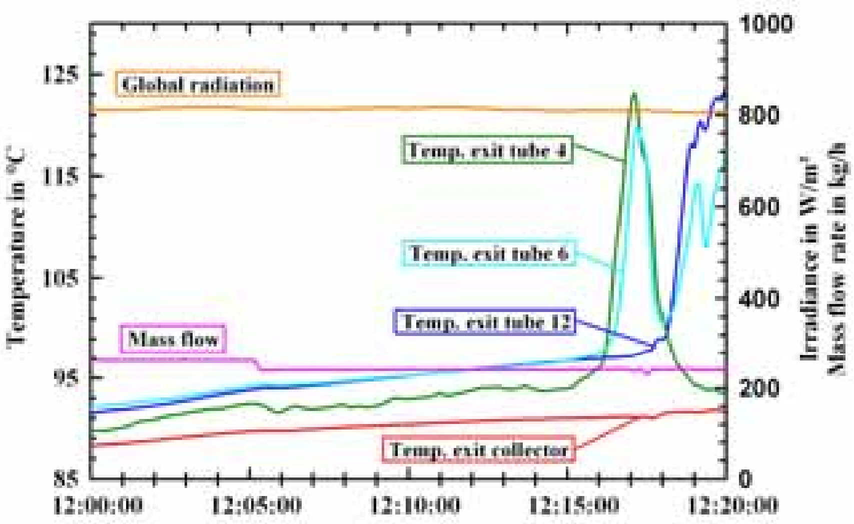

Fig. 2. Temperature patterns as well as mass flow and global irradiance during an experiment concerning the emergence of partial stagnation versus time of the day

The mass flow was gradually reduced during the experiment starting from 500 kg/h. Despite an approximately constant global irradiance level this led to rising outlet temperatures of the collector modules and the individual tubes. At 12:16, about 11 minutes after the mass flow was reduced to 220 kg/h (at 12:05), the temperature began to rise dramatically at the outlet of two of the tubes (tube no. 4 and 6). Prior to this, the first isolated instance of vapour generation occurred indicating the beginning of partial stagnation. The resulting vapour bubble obstructed the fluid flow through the tubes concerned, leading to a heating-up of the fluid mass contained in these tubes. In the following two minutes the hot fluid is pushed out of the tube into the manifold, whereby the vapour condenses, while cold fluid at collector inlet temperature flows into the tube. The temperature peak between 12:16 and 12:18 indicates the flow of hot fluid passing the sensor at the tube outlet.

The temperature rise at the first appearance of partial stagnation is typical for the investigated collector tubes with coaxial absorber pipes. The pipe-in-pipe structure leads to an internal heat exchange between inner and outer pipe and thus causing a temperature profile with the highest temperature not at the outlet but somewhere inside the outer absorber pipe. Under low mass flow conditions the temperature difference between outlet and maximum temperature increases up to values above 30 K. Therefore the first evaporation appears inside the tube while the outlet temperature is still far below the boiling point. A detailed description of this effect is published in [3] and is the topic of a companion paper of this conference [4].

Effectively, partial stagnation begins to occur in those tubes with the lowest tube mass flow rates. The mass flow distribution of the collector group is unequal due to locally changing pressure drops between distributor and collector of the manifold. Fig. 3 shows the mass flow distribution at 500 kg/h for a collector group of 60 tubes with a one-sided connection. This distribution was calculated indirectly with pipe outlet temperatures measurements from more than 40 experiments. The diagram specifies for each tube the ratio of the particular tube mass flow rate to the averaged flow rate of all tubes in the collector group (a mass flow ratio of 1 for a tube means, that the mass flow through this tubes is the complete collector mass flow rate divided by the number of parallel tubes).

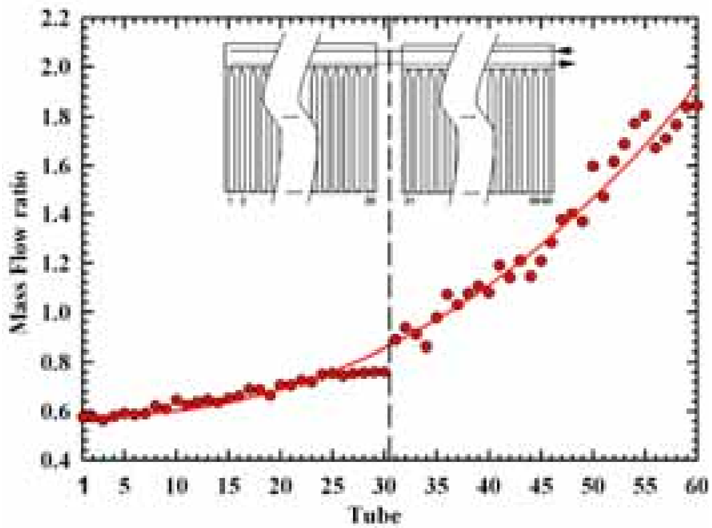

Fig. 3. Mass flow distribution in a collector group consisting of 60 tubes

The tube nearest to the collector connection shows the highest mass flow while the tube farthest away has only 30% of this value. In practice strong variations from the shown mass flow distribution are possible due to trapped air or solid particles in individual tubes. A non-uniform flow distribution occurs at a reverse-return connection, too. In that case, the mass flow rate is lowest in the middle and highest in the outer tubes. However, the differences are less pronounced than with one-sided connected tubes like in Fig. 3.

With the method described above and the experimental procedure shown in Fig. 2, the mass flow rate, at which the first occurrence of partial stagnation is observed, can be determined for different global irradiance levels. Fig. 4 shows the identified mass flow rates as a function of global irradiance and with three different levels of dissolved gas content in the heat transfer fluid. Gas content specifies the amount of gas dissolved in the heat transfer medium measured at 20°C.

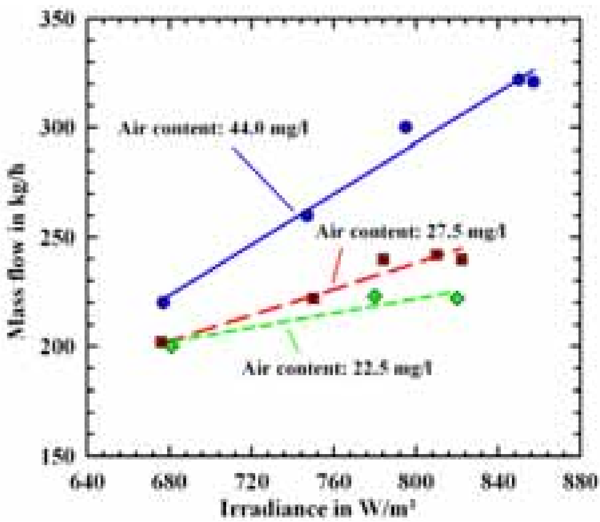

Fig. 4. Mass flow rate, below which partial stagnation has been observed, depending on global irradiance level at different levels of gas content of the fluid

The experiments show, that

• a high gas content,

• a one-sided collector connection and

• low system pressure

are favourable for the development of partial stagnation.

Further investigations were carried out to find out the effect of partial stagnation on the collector group performance. For this, collector efficiency was measured while partial stagnation of different intensities occurred. This was compared to an efficiency curve, previously determined on the test collectors in accordance with the EN 12975-2. Fig. 5 shows the efficiency curve at 900 W/m² with an expanded uncertainty range[2]

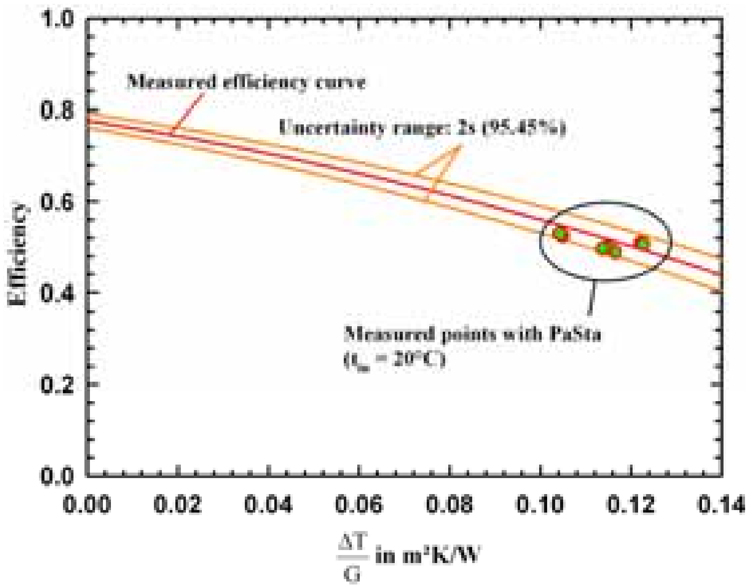

Fig. 5. Efficiency curve at 900 W/m2 with an expanded uncertainty range and efficiency readings during partial stagnation

The efficiency readings during partial stagnation are within the uncertainty range of the efficiency curve without partial stagnation. This means that no significant efficiency reduction due to partial stagnation is perceptible. Further measurements confirm this behaviour even in the case that 50 of the 60 tube are operated at partial stagnation conditions. Fig. 6 shows such an experiment with a high intensity of partial stagnation. At a high global irradiance of 900 W/m² the collector inlet temperature was set to 125°C and the mass flow rate was decreased gradually starting from 500 kg/h.

[2] Expanded uncertainty was calculated with the double standard deviation. This corresponds to a confidence interval of 95.45%.

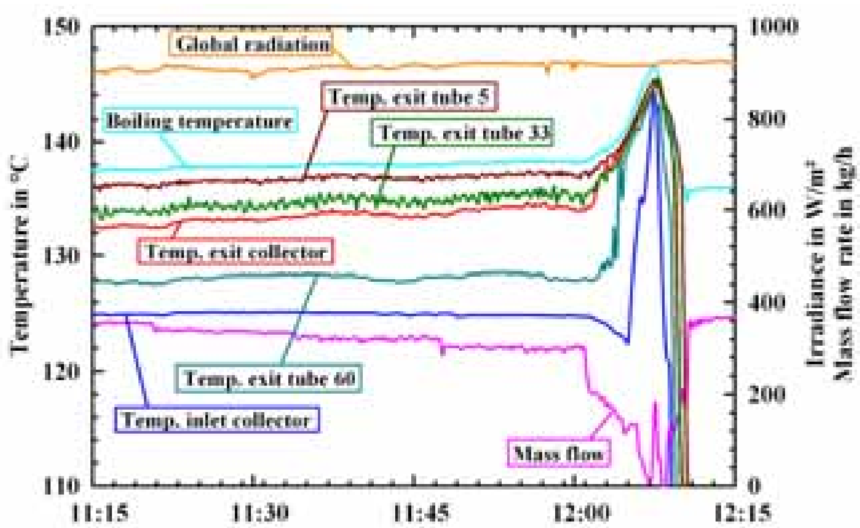

Fig. 6. Experiment to generate partial stagnation of high intensity

The diagram shows global radiation, mass flow rate, collector inlet and outlet temperature as well as the boiling temperature of the fluid[3]. Additionally the diagram displays three tube outlet temperatures. These three temperatures are exemplary for a group of several other tubes.

• Tubes 1 to 30 (represented by tube 5): The tubes are situated opposite to the collector connection and therefore the tube flow rates are lower than the average flow rate in case of no vapour generation (compare Fig. 3). The measured temperatures at the tubes outlets are 1-2 K below boiling point. These tubes permanently generate vapour.

• Tubes 50 to 60 (represented by tube 60): The tubes are situated near the collector connection and therefore the flow rates are significantly higher than the average flow rate. The temperatures are slightly (up to 3 K) above the collector inlet. The fluid flows through these tubes without vapour generation.

• Tubes 31 to 49 (represented by tube 33): The tube flow rates are close to the average flow rate. The tube outlet temperatures are slightly higher than the collector outlet. During the experiment the temperatures show an intermittent pattern. These tubes generate vapour but in contrast to the tubes 1 to 30 larger quantities of vapour condensate inside or at the outlet of the tubes.

15 Minutes after reducing the mass flow rate to 300 kg/h the temperature of all tubes and the collector in- and outlet temperature increase rapidly. Simultaneously the pressure increases (visible by the increase of the boiling temperature) and the total mass flow rate decreases. Temporarily the collector mass flow rate is 0 kg/h while the fluid flows through the bypass connected parallel to the collector group. The experiment was terminated by increasing the collector mass flow rate manually.

This example shows the risk that partial stagnation passes into full stagnation while the collector pump is still running. At full stagnation the collector efficiency is 0. Furthermore, the steam production power in this case is very high if compared to standard stagnation conditions while the pump is off.

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[3] The collector fluids boiling temperature was determined with product data depending on the pressure at collector plane.

4. Discussion

Partial stagnation occurs particularly in large solar thermal systems with different pressure losses and mass flow rates in the subfields. Apart from a non-uniform flow distribution caused by the hydraulic conditions, an unequal flow may occur due to trapped air or solid particles in the collectors groups. Large solar thermal systems are often used in high temperature applications (for instance solar cooling or process heating). The high temperature level further promotes the development of partial stagnation.

The measurements at ISFH show no significant efficiency reduction by partial stagnation at a horizontal collector slope. It may be concluded that the generated steam bubbles lead to a two-phase flow inside the collector tubes. This two-phase flow releases its energy by condensation in the colder parts of the tubes or in the header.

Further measurements at positive collector slopes (header above tubes) confirm this behaviour. At a negative collector slope the vapour bubbles may lead to a blockage inside the tube. With this the vapour prevents a flow through the tube thus reducing the collector efficiency.

Independently of the collector slope partial stagnation can lead to full stagnation in parts of the collector field, as shown in the experiments. In this case the fluid would flow just through a part of the collector field while no flow and no removal of useful heat is taking place in the parallel connected parts.

In any case partial stagnation leads to an unstable operation and a high load of the collector fluid and should be avoided. Reducing the risk of partial stagnation could be achieved by:

- Optimizing the hydraulic conditions
    - Hydraulic balancing of the whole collector field and the subfields
    - Change the collector connection from one-sided to reverse-return connection
- Increasing the overall mass flow to increase the flow rates in the low flow parts of the collector field
- Reduction of the content of dissolved gas using a vacuum degassing unit
- Effective removal of air bubbles and solid particles by
    - Installation of an air and / or dirt separator
    - Increasing temporarily the mass flow rate
- Realizing a higher boiling temperature by
    - Increasing the operating pressure

These measures can avoid a frequent and increased appearance of partial stagnation in large solar thermal systems. However, each of the measures mentioned should be verified for its suitability in the particular system.

5. Acknowledgement

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