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DSG Under Two-Phase and Stratified Flow in a Steel Receiver of a Parabolic Trough Collector

The bending of a receiver tube in two-phase flow under stratified conditions when water is first introduced to the hot steel receiver of a 14.5-m long parabolic trough concentrator is presented in this paper. Thermal gradients were observed on the absorber wall at the inlet of the receiver tube during the boiling of water, at low mass flow of 1.6 $\times 10^{-5}\ m^3/sec$ *(1 liter/min), and low pressure* ($4\times10^2\ kPa$)*. It should be noted that the solar concentrator was focused on the receiver tube, which contained static air before the water was introduced. The introduction of the water produced a change in the temperature difference between the upper and lower sides of the receiver, from 40-60 K to much lower temperatures, in about 45 seconds. The bending of the steel receiver tube occurred when the two-phase flow began. Maximum deflection was observed when the thermal gradient reached a minimum value. We conclude that, when the flow of steam, water, and air exist in a stratified pattern, the combination of these three elements produces the bending phenomenon. The theoretical model, developed to evaluate the experimental data, confirms that the change in temperature gradient produces the bending of the steel receiver tube during this transient stage.* [DOI: 10.1115/1.1463734]

1 Introduction

May and coworkers [1,2] have studied flow instabilities for two phase flow carried out in parabolic trough concentrators. The different flow patterns encountered in a two-phase flow in horizontal pipes have been discussed in many references [3]. These flow patterns can be bubble, plug, stratified, wavy, slug, annular, and spray. Maps of these flow patterns have been obtained for flow conditions of superficial liquid velocity and superficial gas velocity. In a specific manner, a map for heat transfer and fluid flow in a horizontal solar receiver tube has been described by Zarza et al. [4]. This map shows that the stratified pattern for a superficial liquid velocity is in the range of 0.001 to 0.1 m/s and for the superficial gas velocity is in the range of 0.04 to 9 m/s. This pattern has the disadvantage of creating a heat transfer coefficient on the liquid side 10 to 15 times greater than the gas film coefficient, which generates an important circumferential temperature gradient.

Other laboratory experiments and mathematical models have been carried out by others related with circumferential temperature gradients. Goebel and coworkers [5,6] have shown that in stratified flow the temperature difference between the lower and the upper sides of the pipe can be inverted depending on the position of the sun. Their simulation studies indicate that very early in the morning the difference in temperature can be on the order of 60 K with a pressure of 60×10^2 kPa with the upper side warmer than the lower side. At noon, the temperature difference can be 9 K with a pressure of 30×10^2 kPa with the lower part hotter than the upper one. According to the same papers, the heat transfer properties of steam at lower pressure are poorer than at higher pressures. This indicates that the temperature differences across the receiver tube could be worse, greater at lower pressures. Some similar results have been obtained by Hahne et al. [7] with different mass flow densities and for pressures in the range of 30×10^2 to 100×10^2 kPa.

Almanza et al. [8] reported the deflection of a steel receiver tube under field conditions with low flow, 1 liter/min (1.6×10^{-5} m^3/sec) and low pressure (4×10^2 kPa). The bending was observed to be 6.5 cm in segments of the absorber of 2.9 m long. As a consequence, the deflections in the 5 segments of total length of 14.5 m were observed to produce a wave shape, starting in the inlet and ending in the outlet of the absorber of the parabolic trough.

At low powers, 1 kW up to 60 kW, the steam motors are usually a good option for mechanical and electrical energy generation. These engines work with low pressure (from 6×10^2 to 30×10^2 kPa) and low consumption steam conditions from 60 kg/hr to about 1000 kg/hr. As a result, it is important to understand the two-phase flow under stratified conditions in steel absorbers under low pressure conditions. Almanza and Lentz [9] have reported the possibility of producing electrical and/or mechanical energy using DSG in parabolic trough solar concentrators. This conversion is achieved using a 2.24 kW steam, Stuart Swan motor with a two-piston engine type through a high efficiency electric generator of low rpm ($\sim$900 rpm) used in wind technology. The steam was produced using copper absorbers to eliminate any problem related with thermal stress produced under two-phase flow and stratified conditions. As was shown by Almanza et al. [8], if the steel pipe is replaced by a copper pipe, the bending is so small that it can be ignored. This decrease in bending is a result of the difference in thermal conductivity, which for copper is 7 times higher than that of steel. So, the bending effects are canceled, and when the two-phase flow is produced no problems are detected on the steam production at low pressure conditions. Furthermore, the deflection of the steel receiver is so high that the glass envelope breaks when the two-phase flow starts, while for the copper absorber the deflection is 2 or 3 mm as discussed by Almanza et al. [8].

However, as noted by Almanza et al. [8], copper absorbers are not the best option because with time this metal can be converted to soft annealed copper affecting its mechanical properties. As a result, it is important to understand the behavior of steel absorbers, which do not degrade as easily as copper ones, under two-phase stratified flows conditions. Additionally, steel can work at higher pressures than the copper. It should also be mentioned that the copper only can work up to 17×10^2 kPa according to ASHRAE [10]. If the behavior of steel is understood, it can be combined with another metal like copper to form a bimetallic absorber as discussed by Valdés et al. [11]. The behavior of these

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bimetallic receivers has been mathematically modeled and they have shown to be another option for absorbers in DSG.

The results of the experiments that document the bending of the receiver tube are described in this paper. During such experiments, under good conditions of beam irradiance and low wind, the temperature difference between the upper and lower sides of the absorber changed from about 40-60 K to much lower temperatures (4-15 K). This phenomenon is explained with a mathematical model developed by Valdés et al. [11].

2 Experiment

A parabolic trough module 14.5-m long and having an aperture of 2.5 m was used in the E-W orientation to perform a two-phase flow experiment. The focus of the parabolic trough is located 0.625 m from origin of the parabola. A mild steel absorber type SAE 1020 was used (C: 0.18-0.23, Mn: 0.30-0.60, P: 0.040, and S: 0.050; thermal conductivity 52 W/mK; modulus of elasticity 205 GPa; coefficient of linear expansion 11.7×10^{-6}/K), with 2.54×10^{-2} m nominal diameter ($\phi_o=2.92$ cm and 1.9 mm wall thickness). This receiver was covered with black chrome ($\alpha=0.95$, $\varepsilon=0.13$). Additional details about the concentrator can be found in Almanza et al. [8].

Two type K thermocouples with bayonet and pipe-clamp adapters were located on the upper and lower sides of the absorber at the middle of each 2.90-m section of 14.5 m long receiver tube. In some experiments, two additional thermocouples were used on the front and back side of the receiver. This means that 4 temperatures were evaluated on the wall of the absorber. These two last redundant thermocouples always gave values between the upper and lower temperatures on the pipe at noon time. All of the measurements were carried out without Pyrex glass tube envelopment around the receiver pipe.

Figure 1 shows a detailed schematic of the position of the thermocouples on the surface of the absorber. This method assures that the temperature measurements were on the surface of the absorber and did not interfere with the beam irradiance when the thermocouples were in the position where the solar irradiance was reflected to the absorber. Tests were carried out 20 times, which consisted of shadows on the thermocouple produced by a dark band on the parabolic trough mirror. This was done to avoid the reflection of the solar beam on the thermocouple and to check that the temperature did not change on the absorber with and without such band.

The deflection of the absorber was measured with a millimeter scale and observed with a theodolite. When the water was introduced into the tube and the bending started, temperature and displacement measurements along the receiver tube were carried out every 15 seconds.

The inlet cold water was supplied into the absorber at 20°C (293.15 K) with a flow of about 1 liter/min at different pressures, from 0.07×10^2 to 4.14×10^2 kPa (gauge). As it has been mentioned previously by Almanza et al. [8], the average beam irradiance is 866 W/m^2 measured with a rotating shadow band pyranometer which is used to calculate the direct normal irradiance. All the measurements were carried out around noon in the second half of April. The concentrator was almost on the horizontal position and the absorber was heated from below only with static air until temperatures on the order of 170°C on the lower side and 140°C on the upper side of the absorber were reached.

3 Results and Discussion

Figures 2 and 3 are two representative plots of the experimental data obtained on two different days. The upper part of the plots shows the temperatures along the absorber, and the lower part is the difference between the upper and lower temperatures. The local measurements were made every 15 seconds. At the beginning of the experiment the parabolic trough was focussed without any water, only static air was in the absorber until the desired hot temperature was achieved. Figure 2 shows that under this condition the temperature difference was 35 K, which corresponds to the first section of the absorber, while Fig. 3 shows 38 K, which corresponds to the last section of the same absorber. During the heating of the absorber with static air a small deflection of the pipe on the order of 2-3 mm in each section was observed.

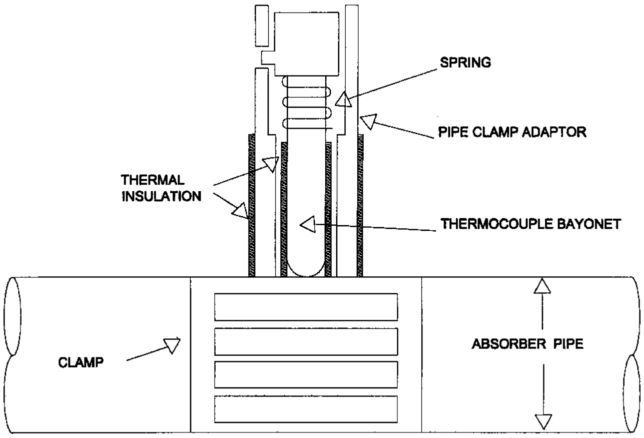

Fig. 1 Arrangement of the thermocouples on the absorber pipe

When low water flow (1 liter/min) started to go into the absorber and reached the middle of the first section, the temperature difference started to come down. After 60 seconds a difference of 4 K was observed (see Fig. 2), and the maximum displacement (bending) of 4.5 cm occurred after 67 seconds. After that, the temperature difference started to increase again to about 20 K and the receiver returned to its original position. This means that the two-phase production finished in this section and only hot water was circulating to the next section of the absorber (from 2.9 m to 5.8 m length of the receiver)

Figure 3 shows a similar behavior; it means a deflection, a return to its original position and a change of temperature difference were measured at the last section of the absorber (from 11.6 m to 14.5 m), with a higher temperature difference at the beginning (38 K) and a temperature drop of 18 K. The displacement of the absorber tube was about 3.6 cm. After all transients were completed and the stored heat in the receiver tube was removed, the absorber no longer was in a two-phase flow regime and only hot water was produced in this module of 14.5 m length. So, the deflection moved from the inlet to the outlet of the module like a wave, starting in the first section and ending in the last one, as previously described by Almanza et al. [8]. This means a deflection and a return to its original position in each section were observed, one after another, in the parabolic trough module, which has five sections.

The maximum temperature difference reached in these type of experiments was about 60 K, due to different solar irradiance and wind conditions. During these experiments, the insulating glass envelope was removed from the steel absorber during the measurements. The experiments were carried out on calm or low wind days, because on windy days it was not possible to achieve temperatures higher than 100°C on the lower part of the absorber. When two additional thermocouples were located on the front and back of the absorber, the temperatures measured with these thermocouples were between the upper and lower ones at noon time. At least 100 experiments have been made and no appreciable difference has been observed, (the statistics have given a standard deviation with an uncertainty of ±1 K).

As mentioned before, the bending of the pipe only occurs during the start up of the water flow into the absorber pipes. The measurements were made around noon when the parabolic trough

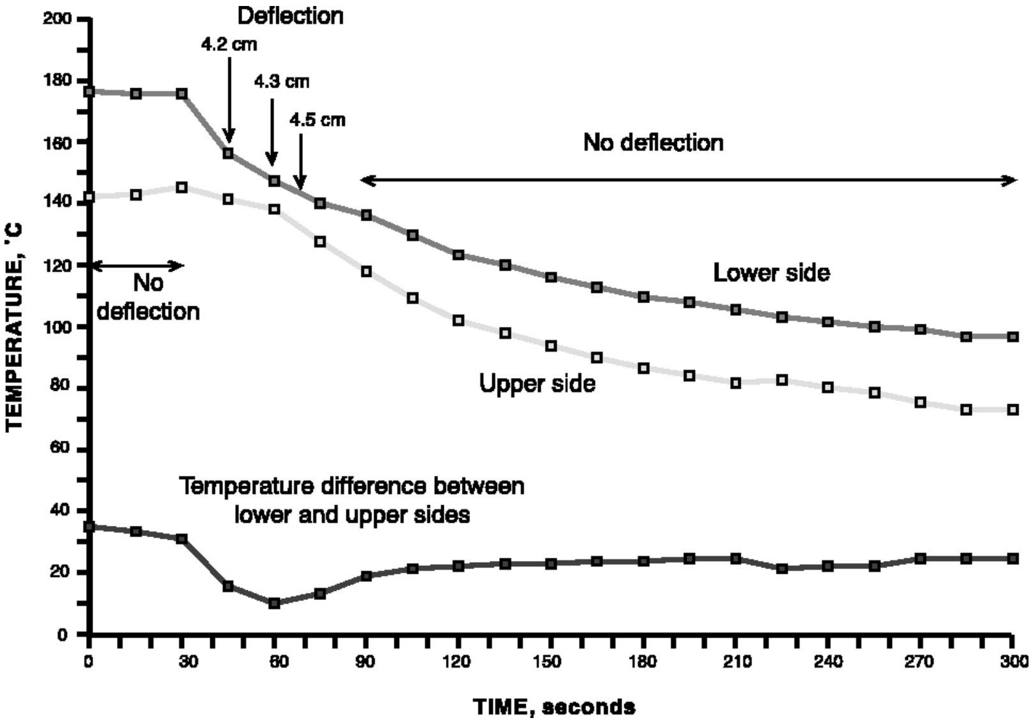

Fig. 2 Deflection of the steel pipe on the first section. Wall temperature on the lower and upper sides of the absorber

was almost in horizontal position. The bending was always upwards and the bending occurred and the tube returned to its original position in a period of about 45 seconds.

According to the mathematical model discussed by Valdés et al. [11], stratified flow generates an important cooling effect in the lower side of the absorber during start up. In order to analyze the circumferential temperature distribution in a receiver pipe under stratified flow conditions, Valdés et al. [11] developed a discrete 2D model that has been used to explain such phenomenon. As discussed in that work, radial temperature differences in the receiver wall are not significant, this conclusion leads us to represent the circumferential temperature profile in terms of a

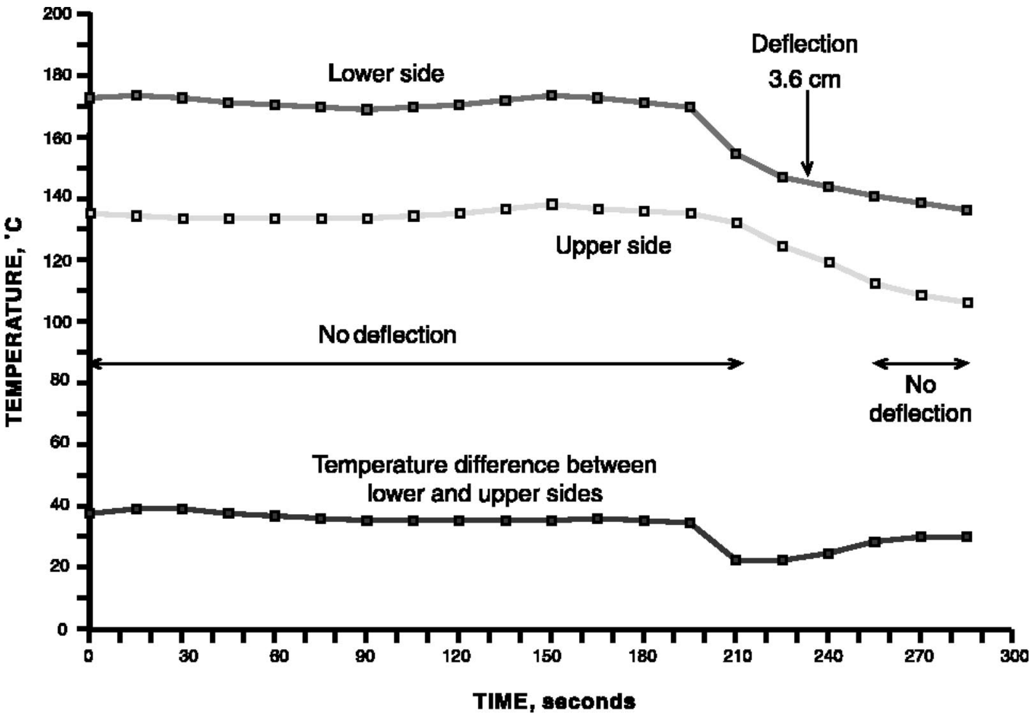

Fig. 3 Deflection of the steel pipe on the last section. Wall temperature on the lower and upper sides of the absorber

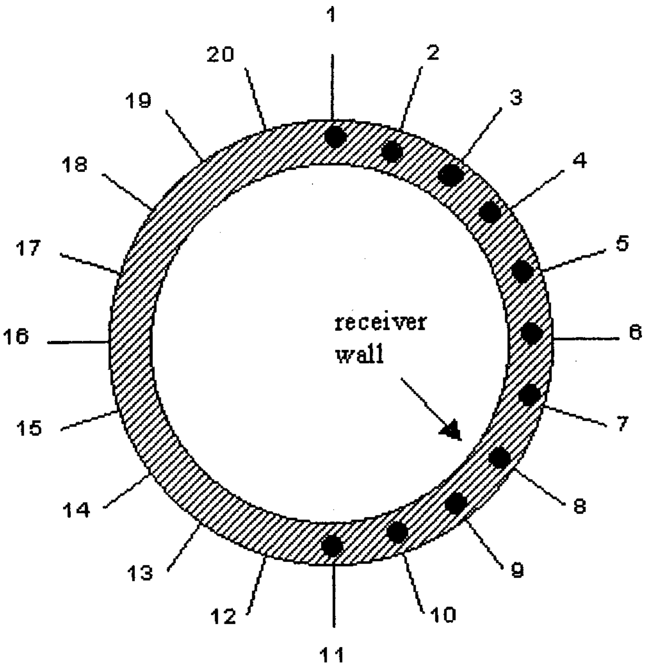

Fig. 4 Node distribution representing the position along the receiver curvature

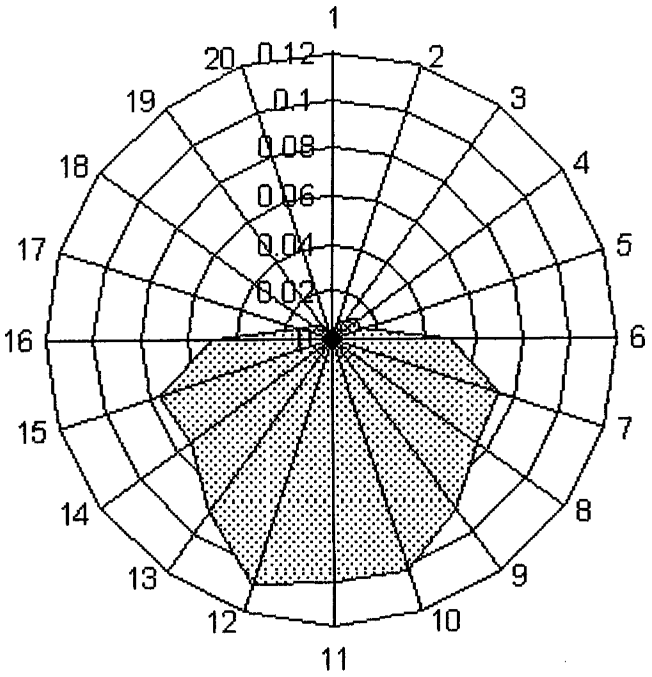

Fig. 5 Polar diagram representing the solar beam irradiance on the receiver. Concentric circles are the fraction of concentrated radiation around a node.

single radial node, shown in Fig. 4.

The lower region of the receiver is always more illuminated than the upper one because the concentrated solar radiation is not distributed uniformly around the receiver tube. Several studies carried out by Almanza et al. [12] and Valdés [13], through laser ray traces on parabolic troughs and using stochastic techniques, have shown that the experimental parabolic troughs described in this work have a radiation distribution like the one shown in Fig. 5. After 20 years of using these concentrators, the aperture of the parabola has changed from 2.5 to 2.525 m and the size of the focal images has increased to about 6 cm, as discussed by Martínez et al. [14], from the original 2.5 cm. Therefore, when the 2.92-cm diameter pipe was deflected by 6 cm, focusing was still observed on the absorber.

Under these circumstances, numerical simulations were made first by considering the air flow along the axial direction of the receiver pipe. The displacement of air along the pipe was a result of the injection of water flow to the absorber pipe. In the first 30 seconds (shown in Fig. 2), the circumferential temperature profile shows a difference of 30 K between the upper and lower parts of the receiver. Since the receiver is mainly heated from below, it is expected to show higher temperature at the bottom. This difference in the wall of the receiver is shown in the air flow curve in Fig. 6 as a solid line between nodes 1 and 11. Node 1 corresponds to the top of the pipe. Solid curves are related to the air flow, which indicates that the water goes into the pipe and starts to displace the air while the broken curve represents the wall temperature due to the water flow in an *open channel* sense. This means that, due to the low flow of water, the stratification of water-air is well defined, from the beginning of the process, and hence the cooling effect that appears at the bottom of the pipe. In addition to the period of boiling and two-phase flow, which happens in about 45 sec, there is an effect of cooling on all the wall because, while the water is boiling and evaporating, more cool water is arriving to the lower part of the receiver. This last effect corresponds to the time of 60 seconds in Fig. 2 and the difference in temperature is only 4 K instead of 35 K at the beginning, with a higher temperature at the bottom with respect to the upper part. It may be discerned that the simulation is in a good agreement with the measurements.

This bending can be as a result of the presence of a stratified flow along with the two-phase flow, that makes the cooling effect on the lower part of the absorber to be more drastic than on the upper part (as can be seen in Figs. 2 and 3). It should be mentioned that the axial contraction of the pipe on the lower part occurs faster and stronger than in the upper and, as a consequence the deflection of the absorber is upwards. This can be explained with the following statement: at the beginning only static air is in the focused absorber that has been heated slowly. In about 30 min, the final temperature difference is reached between the upper and lower part and is on the order of 40K before the water goes into the steel receiver pipe, (as is shown in Fig. 2). Linear expansion is carried out slowly, allowing the pipe to slide over the posts and a deflection of about 2-3 mm is observed in each section. When the water starts to go into the receiver, a fast thermal gradient occurs mainly in the lower side and a temperature difference of only 4 K is reached in 60 sec with a deflection of 4.3 cm. Deflections are not created in the following sections, because only air is flowing

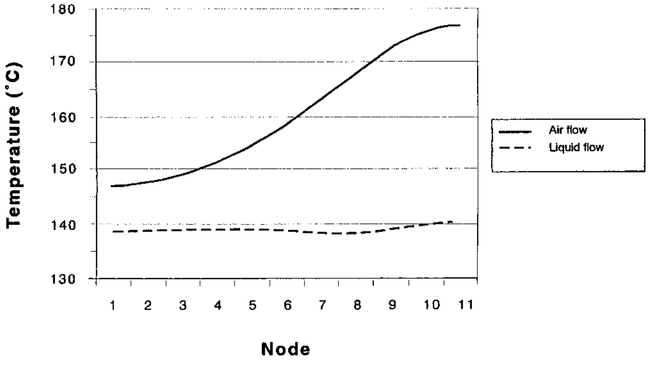

Fig. 6 Predicted wall circumferential temperature profiles on a steel receiver under non-homogeneous irradiance distribution. Node 1 corresponds to the top of the pipe. The solid curve is related to the flow of air, while the broken one is related to the arriving liquid water on an open channel sense.

through the receiver and the water has not yet reached them. As a consequence, the bending is only a local phenomenon and occurs when fast thermal gradients are observed, generating thermal stresses. A sliding back on the posts of the absorber of about 4-5 mm was also observed over the first section, toward the side where the pipe is bending.

However, there can be other effects that contribute to such phenomenon, which will be studied in the future, e.g., when the beam irradiance is focused laterally on the absorber, mainly during the winter in high latitudes, the thermal gradients are going to be completely different.

It may be concluded that two types of bending can occur on the receiver; one due to the thermal expansion of the absorber when heated with static air from ambient temperature to over 140°C. This bending is negligible (2-3 mm) in each section. The other one, due to a local fast thermal gradient in each section of the absorber that is responsible for the deflection described in this paper.

4 Conclusions and Suggestions

We conclude from this work that the deflection of the solar receiver tube carried out under a transient state at start up, when the receiver is hot, is generated by one or both of the following effects:

(a) the presence of a stratified pattern due to a change of phase of the flowing water; or
(b) the flow of subcooled water into a partially filled receiver in an *open channel* sense.

Under both conditions, the mathematical model predicts the change of the temperature gradient, which induces a thermal stress. Such gradients produced under these conditions will generate the bending of the absorber steel pipe.

The next step in this experimental research is the development of a bimetallic receiver with an external steel pipe joint with an internal copper pipe. Almanza et al. [15] have shown with an analytic model that the behavior of this bimetallic pipe can be the solution to develop a receiver that can work at low pressure and stratified two-phase flow. The next step of this project will be the construction of the bimetallic receiver and the study of its behavior under different conditions (pressure, temperature, and heating from below).

Since the experiments have been carried out at low pressures and low flow, the partially filled flow pattern (water+air) is a relevant factor that produces gradient changes. At low and high pressures, when the pipes are fully filled, the most important factor to produce the bending may be the change in flow pattern to the stratified one. However, this last phenomenon must be studied carefully in order to know if it can cause the same effect.

In a real solar power plant with steel receivers that work at low pressure and low flow of water, the deflection will be during the transient stage only. In experiments carried out recently, it has been possible to observe that if some additional modules are connected, the steam production in steady state causes no problems regarding the deflection, as has been demonstrated by Flores [16], because the boiling phenomenon changes probably to a boiling/evaporation process. The details in steady state will be published in the near future, as well as the behavior of the bimetallic receiver.

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Nomenclature

C = carbon
Mg = manganese
P = phosphorus
S = sulfur
E-W = east-west
α = absorptance
ε = emittance
ϕ_0 = external diameter of the absorber

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