

Experimental Investigation of Heat Losses in Hydrogen-Doped Parabolic Trough Receivers

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Abstract. This study investigates the impact of hydrogen presence in the annulus space of heat-collecting elements (HCEs) used in parabolic trough solar power plants. Hydrogen, formed during degradation of the heat transfer fluid diphenyl oxide/biphenyl (DPO/BP), can permeate into the annulus and significantly increases heat loss due to enhanced conductive heat transfer. Following the resistance heating method defined in the technical specification IEC TS 62862-3-3, heat loss measurements were conducted on HCEs before and after hydrogen doping at various absorber temperatures (100–400 °C). Results showed heat losses up to four times higher in hydrogen-doped receivers, reaching 867 W/m at 400 °C, compared to 211 W/m in evacuated units. Uncertainty analysis confirmed measurement reliability. The data confirms hydrogen's detrimental effect on thermal performance and supports the need for improved hydrogen control in operational solar power plants with parabolic troughs.

Keywords: Parabolic Trough, Solar Receiver, Heat Loss, Heat Transfer Fluid, Hydrogen Formation

1. Introduction

The use of specific heat transfer fluids (HTFs), such as diphenyl oxide/biphenyl (DPO/BP), in parabolic troughs (PT) solar power plants is due to outstanding heat transfer properties and thermal stability up to 400 °C. However, during operation, DPO/BP forms permanent gases such as hydrogen, methane, and carbon monoxide with an increased rate in aging time [1]. One of the ongoing operational and maintenance (O&M) challenges in power plants is controlling hydrogen formation and concentration in the HTF to acceptable levels [2]. This is necessary to prevent the permeation of H₂ into the evacuated annulus space between the glass envelope and the absorber tube of the receivers (or heat-collecting elements, HCE) installed in the solar field. The presence of H₂ in this annulus space increases heat loss due to conductive heat transfer through the gas (Knudsen effect), negligible when there is vacuum in this zone, and originates an increase of the temperature of the glass envelope, which is called “hot tube phenomena”, which can also lead to a break in the glass envelope of the HCE.

Previous studies have reported modeled or specific experimental values of heat loss with different annulus content for gas-filled HCEs in solar fields [3]. This work presents experimental heat loss and glass temperature data of untreated HCEs and of the same HCEs after they were deliberately doped with H₂, each time measured in a laboratory-controlled environment.

2. Methods and experimental set-up

The heat loss measurements of HCEs were conducted in a lab environment, using the HEA-TREC test bench [4] located at Plataforma Solar de Almería (PSA). The HCEs under investigation were Schott PTR®70 Gen 2 units, provided by CIEMAT from the stock available for PSA's outdoor test facilities with PTs. These HCEs were subjected to controlled manipulations to introduce hydrogen (H_2) into the evacuated annulus space. The primary goal was to assess the effect of hydrogen on heat losses, given the significant operational challenges posed by hydrogen permeation into the annulus.

2.1 HCEs characteristics

The receiver tubes (HCEs) tested were standard PTR®70 Gen 2 units (see Figure 1), which are well known and currently used in commercial solar power plants with PTs (eg, in Spanish solar thermal power plants). This type of HCE is made up of two concentric cylinders, an absorber tube, and a glass envelope. The inner one is the absorber tube, which is made of stainless steel and is coated with a selective coating to achieve high solar absorptance and as low as possible emittance. The outer one is the glass envelope, which is a borosilicate glass with antireflective coating on the inner and outer surface to increase the transmittance of solar radiation. The annular space between the absorber tube and the glass envelope is evacuated having a pressure of about 10^{-4} mbar. To delay the vacuum degradation, getters are located into the vacuum annulus to absorb a certain quantity of incoming gases into this space. A summary of the main characteristics of this type of HCE is listed in Table 1 [5]. Initially, four units of HCEs were selected for the test.



Figure 1. View of one of the PTR® 70 Gen 2 HCE tested.

Table 1. Characteristics of PTR® 70 Gen 2 HCEs [5].

Parameter	Value
Absorber tube length at 23°C (m)	4.060
Absorber tube internal diameter (m)	0.066
Absorber tube external diameter (m)	0.070
Absorber tube material type	Stainless steel grade 321
Glass envelope internal diameter (m)	0.114
Glass envelope external diameter (m)	0.120
Glass envelope material type	Borosilicate glass
Heat loss (at $T_{\text{absorber}} = 400$ °C) (W/m)	223 ± 10
Emittance (at $T_{\text{absorber}} = 400$ °C) (-)	0.094 ± 0.005

2.2 Hydrogen doping of the HCEs

For hydrogen doping, the four units of HCEs were sent to the DLR laboratory in Cologne (Germany). Manipulation started by drilling a hole into one of the expansion bellows to introduce H_2 into the annulus space. Sections of 8 mm pipes with valves were welded to the expansion bellows and equipped with blind plugs to close the space and maintain the atmosphere of H_2 inside the annulus (see Figure 2). The HCEs were doped with hydrogen at a pressure of 1 mbar at 400 °C operation conditions, which implies the corresponding saturation of the getters inside the HCE. From the original set of HCEs selected for the test, one of them broke during manipulation, and finally three of them composed the set for the study. The procedure of manipulating HCEs through the expansion bellows to control the atmosphere in the annulus space between the absorber tube and the glass envelope of HCEs, had been previously used in previous research with good results [6].



Figure 2. HCEs end sections after hydrogen doping at DLR. 8 mm pipes with valves and blind plugs mounted to the HCEs. (picture: DLR)

2.3 HEATREC test bench

The HEATREC facility allows for precise evaluation of heat loss in solar receiver tubes under controlled atmospheric conditions. This test bench setup comprises a chamber, heating system, cooling system, and a data acquisition system (SCADA) (see Figure 3) [4].

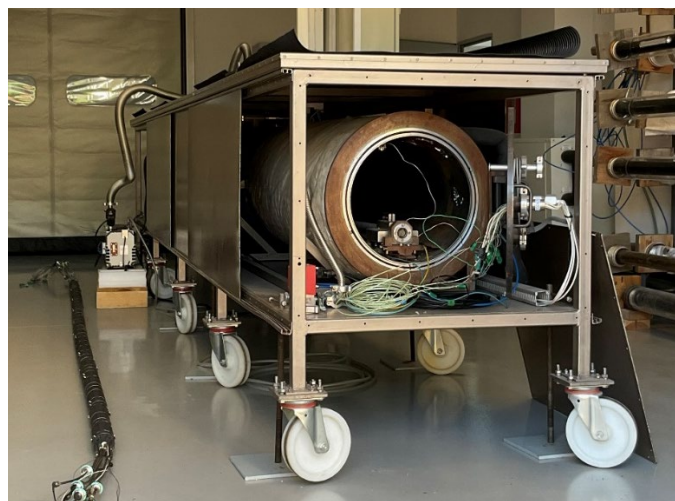


Figure 3. HEATREC test bench for heat loss measurement of HCEs.

The chamber is a hollow steel cylinder (5 m long, 0.4 m in diameter), where the receiver tube to be tested is placed (see Figure 3). A vacuum pumping system is connected to this chamber to allow for the control of vacuum pressure in the inner space of the chamber as low

as 10^{-2} mbar. The purpose of this vacuum system, when it is running during an experiment, is to prevent convective heat losses in the surroundings of the HCE, which may be of interest when testing new evacuated receiver tubes, to get a more accurate measure of radiative heat losses and emittance of the HCE unit under test.

A set of electric heaters, embedded in an aluminum cylinder, is placed in the inner space of the absorber tube of the HCE and provides the heat required to maintain stable absorber temperatures at the desired reference temperature, depending on test conditions. Heat losses are determined by measuring the electrical power supplied to these heaters under steady-state conditions.

The test bench is equipped with temperature sensors to measure the temperature of the aluminum cylinder, absorber tube (from the inner side), glass envelope of the HCE, and ambient temperature inside the chamber. All the equipment and sensors of the test bench are monitored, controlled, and stored from a workstation with a SCADA developed in LabVIEW.

2.4 Heat loss test procedure

The heat loss measurements of the HCEs were carried out in a laboratory environment, using the HEATREC test bench at Plataforma Solar de Almería, according to the resistance heating method defined in the international technical specification IEC TS 62862-3-3.

For this study, whose purpose is to compare the heat losses of untreated and H₂-doped HCEs, the test campaign comprised two series of measurements. Initial HEATREC measurements prior to H₂ doping and repeated measurements after H₂ doping. Each series comprised the measurement of the identical three PTR®70 Gen 2 HCEs (see Figure 1) at absorber temperature of about 100 °C, 200 °C, 300 °C, 350 °C and 400 °C, with a temperature stability of ± 2 °C and chamber temperature controlled at (20 ± 10) °C during at least 15 minutes. For this study, the pressure in the inner of the chamber was atmospheric pressure, i.e. the vacuum system of the test chamber was not running.

The absorber temperature was taken as the average of all the temperatures measured on the inner surface of the absorber tube, where fourteen type K thermocouples were placed [4]. Six type K thermocouples were also placed on the outer surface of the glass envelope, equally spaced along the HCE, three on the top, and three at the bottom. The ambient temperature was calculated as the average of the two temperatures measured on the wall of the test chamber.

The heat loss was calculated as the sum of the electrical power measured by the power suppliers connected to the electrical heaters.

Once the initial measurement series was completed, the HCEs were sent to the DLR laboratory in Cologne, where the HCEs were doped with H₂, as described in Section 2.2. The same HCEs were then returned to PSA for the second series of heat loss measurements, as defined before.

3. Results

The results of the experimental campaign revealed that heat losses increased significantly in the presence of hydrogen (H₂) in the annulus space. Data were collected for three different PTR®70 receiver tubes under the two conditions: without H₂ (vacuum state) and with H₂ introduced at a partial pressure of 1 mbar. Measurements were made for the absorber temperature from 100 °C to 400 °C, and the results showed consistent trends in all receiver tubes.

Table 2 summarizes the main experimental results obtained during the initial and second series of measurement (without and with H₂ in the annulus of the HCEs), including the temperature measurements of the absorber tube and the glass envelope and the results of heat losses. The tests were repeated at least three times.

Table 2. Experimental results of heat loss (HL) measurement of the 3 units of PTR® 70 Gen 2 HCEs tested. T_{absorber}: absorber tube temperature; T_{glass}: glass envelope temperature.

HCE ID	HCE evacuated (unused)			HCE after H ₂ -doping (~1 mbar @ 400°C)		
	T _{absorber} (°C)	HL (W/m)	T _{glass} (°C)	T _{absorber} (°C)	HL (W/m)	T _{glass} (°C)
#1	101 ± 2	8 ± 6	19 ± 2	102 ± 2	15 ± 3	24 ± 2
	101 ± 2	8 ± 6	19 ± 2	102 ± 2	12 ± 5	21 ± 2
	104 ± 2	8 ± 6	21 ± 2	101 ± 2	12 ± 5	24 ± 2
	201 ± 2	30 ± 14	30 ± 2	198 ± 3	107 ± 5	49 ± 2
	202 ± 2	30 ± 14	30 ± 2	199 ± 2	107 ± 5	48 ± 2
	200 ± 2	30 ± 14	29 ± 2	202 ± 2	107 ± 5	50 ± 2
	300 ± 2	87 ± 20	47 ± 3	299 ± 4	484 ± 3	126 ± 4
	300 ± 2	87 ± 20	46 ± 2	300 ± 4	484 ± 3	128 ± 4
	301 ± 2	88 ± 20	45 ± 3	300 ± 4	484 ± 3	132 ± 4
	350 ± 2	138 ± 20	58 ± 3	350 ± 4	651 ± 3	156 ± 4
	352 ± 2	138 ± 20	58 ± 3	349 ± 5	666 ± 5	146 ± 3
	350 ± 2	138 ± 20	59 ± 3	352 ± 4	649 ± 3	157 ± 4
	400 ± 3	211 ± 20	73 ± 4	398 ± 4	867 ± 5	169 ± 3
	401 ± 3	210 ± 20	72 ± 4	399 ± 4	872 ± 5	169 ± 3
	400 ± 3	211 ± 20	74 ± 4	400 ± 5	867 ± 5	169 ± 3
#2	103 ± 2	10 ± 7	20 ± 2	103 ± 2	10 ± 5	19 ± 2
	101 ± 2	10 ± 7	19 ± 2	102 ± 2	10 ± 5	22 ± 2
	101 ± 2	10 ± 7	19 ± 2	104 ± 2	10 ± 5	31 ± 2
	201 ± 2	39 ± 7	30 ± 2	203 ± 2	39 ± 10	31 ± 2
	201 ± 2	39 ± 10	29 ± 2	201 ± 2	41 ± 12	29 ± 2
	200 ± 2	39 ± 10	27 ± 2	203 ± 2	41 ± 12	32 ± 2
	300 ± 2	100 ± 12	49 ± 4	297 ± 3	282 ± 10	91 ± 2
	301 ± 2	100 ± 20	47 ± 3	299 ± 3	350 ± 5	107 ± 2
	300 ± 2	100 ± 20	46 ± 3	299 ± 3	292 ± 5	93 ± 2
	350 ± 2	150 ± 20	58 ± 4	349 ± 3	630 ± 7	157 ± 3
	351 ± 2	150 ± 20	59 ± 4	349 ± 4	625 ± 5	156 ± 3
	351 ± 2	150 ± 20	60 ± 4	353 ± 3	622 ± 3	151 ± 2
	399 ± 2	230 ± 20	75 ± 5	398 ± 3	824 ± 7	181 ± 3
	400 ± 2	230 ± 20	76 ± 5	398 ± 4	822 ± 7	182 ± 3
	399 ± 2	230 ± 20	75 ± 5	398 ± 4	822 ± 5	181 ± 3
#3	102 ± 2	10 ± 5	21 ± 2	103 ± 2	11 ± 2	20 ± 2
	102 ± 2	10 ± 5	23 ± 2	101 ± 2	10 ± 3	21 ± 2
	102 ± 2	7 ± 7	22 ± 2	103 ± 2	10 ± 3	22 ± 2
	202 ± 2	32 ± 12	33 ± 3	201 ± 3	46 ± 3	33 ± 2
	200 ± 2	32 ± 12	26 ± 2	201 ± 3	46 ± 3	30 ± 2
	201 ± 2	32 ± 12	31 ± 2	203 ± 3	46 ± 3	36 ± 2
	299 ± 2	90 ± 20	48 ± 3	298 ± 4	315 ± 2	99 ± 4
	302 ± 2	90 ± 20	45 ± 3	298 ± 5	364 ± 2	111 ± 4
	301 ± 2	90 ± 20	46 ± 3	302 ± 5	384 ± 2	119 ± 4
	350 ± 3	140 ± 20	59 ± 4	350 ± 6	602 ± 3	152 ± 5
	351 ± 3	140 ± 20	59 ± 5	353 ± 5	578 ± 3	150 ± 5
	350 ± 3	140 ± 20	60 ± 5	348 ± 6	597 ± 3	150 ± 5
	400 ± 3	210 ± 20	76 ± 5	399 ± 5	796 ± 4	177 ± 6
	400 ± 3	210 ± 20	74 ± 5	401 ± 5	796 ± 4	176 ± 6
	400 ± 3	210 ± 20	73 ± 5	399 ± 5	794 ± 4	178 ± 6

3.1 Heat loss without hydrogen

In the initial state (without H_2), the heat losses were primarily driven by radiative effects, with values increasing proportionally to the temperature gradient between the absorber tube and the environment. For instance, at a T_{absorber} of 100 °C, heat loss for receiver ID#1 was measured at 8 W/m, while at T_{absorber} of 400 °C, the heat loss reached 211 W/m. This pattern was similarly observed in the other two tubes (ID#2 and ID#3), with heat losses ranging between 7-10 W/m at the lowest T_{absorber} values and increasing to approximately 230 W/m at the highest T_{absorber} values.

The heat loss under this vacuum condition aligns well with previous characterizations of the Schott PTR®70 Gen 2 HCEs [5] and corresponds to the expected heat transfer behavior of evacuated receiver systems, where radiative losses dominate at higher temperatures.

3.2 Heat loss with hydrogen

When hydrogen was introduced into the annulus space, a significant increase in heat loss was observed because of the additional conductive pathways introduced by the gas. Across all tested tubes, heat loss increased by up to four times, particularly at higher absorber temperatures.

For receiver tube ID#1, at T_{absorber} of 400 °C, the heat loss with H_2 increased to 867 W/m from 211 W/m in the vacuum state, highlighting the substantial impact of hydrogen on thermal performance (see Figure 4). Similarly, the other two receivers exhibited marked increases in heat loss: ID#2 reached 822 W/m (from 230 W/m), and ID#3 recorded 796 W/m (from 210 W/m) under the same conditions.

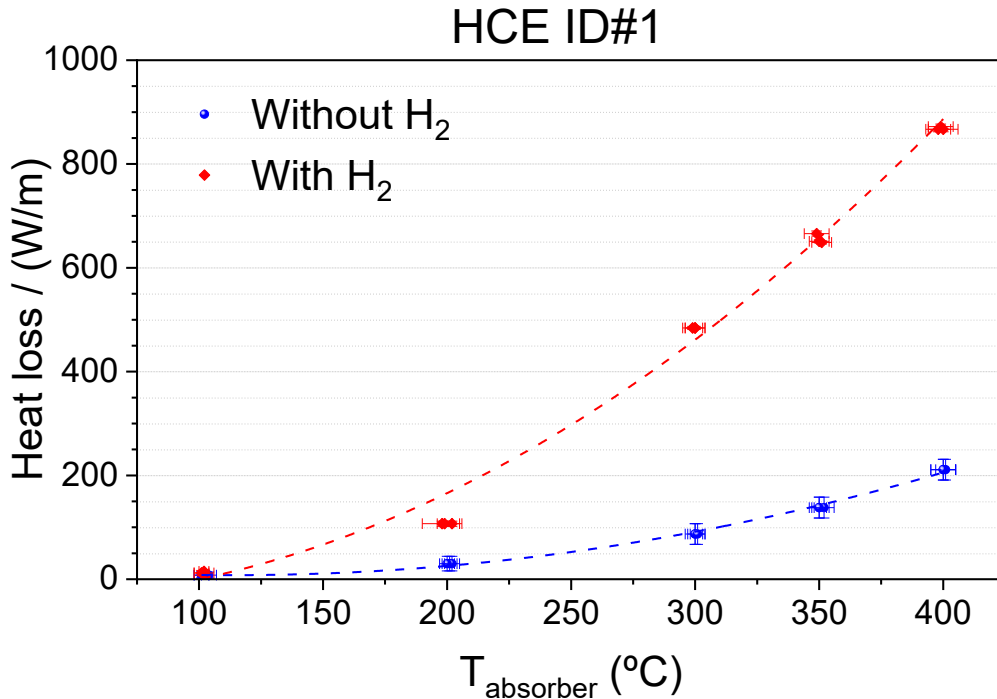


Figure 4. Heat loss measurements comparison for the HCE ID#1.

Data available in Table 2.

3.3 Comparative analysis, uncertainty and data reproducibility

As summarized in Table 2, the increase in heat loss due to hydrogen was negligible at the testing absorber temperature of 100 °C, but was over 600 W/m at the elevated testing temperature of 400 °C, compared to the heat loss under vacuum conditions. This sharp rise in heat dissipation at elevated temperatures is due to conductive heat transfer through the gas in the annulus (Knudsen effect), where the H₂ is confined. These results are consistent with previous studies on gas-filled solar receivers conducted by NREL [3] [7], where even low concentrations of hydrogen dramatically degrade the insulating properties of the vacuum annulus. Comparing the results in Table 2 and also the specific case shown in Figure 4, the increase in heat loss caused by hydrogen, mainly due to the aforementioned conductive heat transfer through the gas, represents three times the heat loss caused by radiation (case without hydrogen).

Uncertainty analysis was performed following GUM guidelines. Type B measurement uncertainties for the thermocouples and power supply systems remained within ± 1.5 °C and $\pm 1\%$, respectively, and were determined using the available information from sensors and data acquisition cards where the sensors and equipment are connected. The uncertainties provided in Table 2 are the combination of statistical uncertainty (Type A) and the Type B uncertainty. This confirms the robustness of the experimental data and ensures that the observed trends in heat loss are reliable. For the initial state (without H₂), the heat losses followed a predictable pattern based on the temperature gradient, while the presence of hydrogen introduced variability and increased heat dissipation due to gas conduction, which also increased the dispersion of the results, as shown in Table 2.

The measurement carried out in the HCEs with H₂ in the annulus space required longer steady-state test periods compared to the initial series. This can be attributed to unsteady H₂ convective gas flow within the glass envelope. This may result from a gradual release of H₂ from the getters or even a re-absorption, possibly caused by changing getter temperatures, which in turn are influenced by the HCE absorber tube temperature -and the instantaneous H₂ pressure.

4. Conclusions

This study confirms the significant detrimental effect of hydrogen permeation into the annulus space of state-of-the-art receiver tubes used in parabolic trough solar power plants. Experimental measurements, carried out using a test bench under controlled conditions and following the resistance heating method of the IEC TS 62862-3-3 specification, showed that the presence of hydrogen at partial pressures as low as 1 mbar causes substantial increases in heat losses due to conductive heat transfer through the annulus gas, as reported in previous studies, and which does not occur in vacuum. The measured heat loss in the hydrogen-filled receivers was not only higher, but also exhibited an increased variability, probably due to gas circulation within the annulus space, making it more challenging to achieve steady-state conditions. Three receiver tubes were analysed in the study and, overall, the increase in heat loss due to hydrogen ranged from negligible at a testing temperature of 100 °C to over 600 W/m at 400 °C. The most critical finding was that at an absorber temperature of 400 °C, heat loss in hydrogen-doped HCEs reached up to 867 W/m, compared to only 211 W/m under evacuated conditions – representing a fourfold increase.

The consistency of the measured data, confirmed by repeated trials and supported by uncertainty analysis, underscores the critical importance of controlling hydrogen generation and permeation in operational solar power plants with parabolic troughs using DPO/BP as heat transfer fluid. These findings reinforce the need for improved hydrogen management strategies and/or receiver tubes to maintain the thermal efficiency and operational longevity of HCEs in solar thermal power plants.

Author contributions

Loreto Valenzuela: Conceptualization, Methodology, Resources, Formal analysis, Investigation, Validation, Writing – original draft, Funding acquisition, Project administration; Rafael López-Martín: Methodology, Data curation, Formal analysis, Resources, Investigation, Writing – review & editing; Carmen M. Amador: Data curation, Resources, Investigation; Christoph Hilgert: Conceptualization, Resources, Investigation, Validation, Writing – review & editing, Funding acquisition, Project administration.

Competing interests

The authors declare that they have no competing interests.

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