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Benoit Fiers, Raphaël Rousseau, Didier Martin, Jean-Jacques Bézian, Olivier Quénard, et al.. Study of an unstructured integrated solar captor - thermal storage for CSP. International journal of energy, environment, economics, 2017, 24 (4), pp.419-436. hal-01686702

HAL Id: hal-01686702

<https://imt-mines-albi.hal.science/hal-01686702>

Submitted on 2 Nov 2020

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STUDY OF AN UNSTRUCTURED INTEGRATED SOLAR CAPTOR – THERMAL STORAGE FOR CSP

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ABSTRACT

An integrated system composed of a solar captor and a thermal storage is presented. Both parts are made of unstructured granular materials, stacked and disposed under a solar concentrator. This system has been devised for being coupled with a “Beam-Down” type solar concentrator. Our first approach for designing that kind of integrated system is to analyze and to optimize both parts separately (the solar captor for one part and the thermal storage in packed bed for the other). Those preliminary studies have been realized thanks to a couple of dedicated experimental devices. Two points are guiding those studies: the economic need for a low cost installation, yielding to a highly unstructured conception of those porous media, and the opportunity to use the very high thermal performances of COFALIT, a product made of asbestos-based retreated waste. The main objective is then to integrate those optimized system in a global integrated device, the stakes of which are presented.

Keyword: solar captor, thermal storage, sensible heat, concentrated solar power

NOMENCLATURE

a	selective layer absorption factor
c_i	i-phase heat capacity, $J.kg^{-1}.K^{-1}$
d	grain mean diameter, m

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e	selective layer thickness, m
h_{vol}	solid-fluid volumic heat exchange, $W.m^{-3}.K^{-1}$
K	porous media permeability, m^2
K_i	porous media inertial permeability, m
P	fluid phase pressure field, Pa
p	emission form factor
T_i	i-phase local temperature, K
u	fluid phase Darcy velocity, $m.s^{-1}$

Greek Symbols

μ	fluid viscosity, $Pa.s$
ρ_i	i-phase density, $kg.m^{-3}$
ε	porous media porosity
λ_i	thermal conductivity, $W.m^{-1}.K^{-1}$
Φ_i	incident flux density, $W.m^{-2}$
σ	Stefan-Boltzmann constant
ϵ	selective layer emissivity

Subscript

f	fluid phase
s	solid phase

INTRODUCTION

The RESCOFIS project is supported by the French ANR and labeled by the DERBI pole. That project is part of the French program that aims to develop CSP power plant of small size, for a low-power decentralized energy production (thermal or electric) in remote site. A comparative study of the pros and cons of the different CSP technologies have been published by the German DLR [1]. Regarding to the power and temperature levels that are aimed in this project, the “Beam-Down” technology (see Figure 1) appears to be interesting for several reasons: it allows a high level of concentration, the acuteness of the solar spot is quite good compared to a more classic Tower Plant, and the installations are simpler and lighter. On the other hand, the main drawback of this technology is the optical loss due to the secondary reflection; but the performance loss can be compared to the thermal loss that would be seen in a Tower Plant, in the descending part of the heat fluid circuit [2].

This project is conducted by IDHELIO, in partnership with EUROPLASMA, ICAM Toulouse and the RAPSODEE Laboratory. The objective is to design and to optimize a solar captor with integrated thermal energy storage, adapted to the “Beam-Down” concentrator technology. Several points have to be respected in this system:

- Both functionalities (solar captor and thermal storage) must be integrated in a simple, compact system.
- This device should allow a direct implantation at the focal point of a “Beam-Down” concentrator, on the ground.
- The storage part should allow an optimized management of the discontinuous solar resource: a day worth of solar resource will allow a continuous production of low power electricity for several successive days.

Industrial objectives consist of a continuous electrical production of about 10 to 100 kW on a 24 hour basis, using a thermal storage and a thermal/electric energy converter, in which a fluid temperature of about 600°C would be reached.

The chosen technology depends on the temperature and power level: those imply two superimposed fixed beds, for both the captor and the storage. The thermal storage will adapt a stratified sensible heat storage technology [3]. COFALIT has been chosen as the granular solid material to fill the storage packed bed: this material is made of asbestos-based retreated waste, and is known for its good thermal properties (high density, high thermal resistance against temperature and thermal shock, see Table 1) [4, 5, 6]. In order to optimize the industrial cost of those systems, an unstructured packed bed made of piled off granular materials for both the captor and the storage is researched [7][8]. Air has been retained as tested heat fluid: a high temperature-resistant fluid is actually required, and the cost requirement yield to a compact, simple system, excluding molten salt and thermal oil. High pressure drops are generally associated to those air-based systems, but using solar concentration allows a small-size device with acceptable pressure drops.

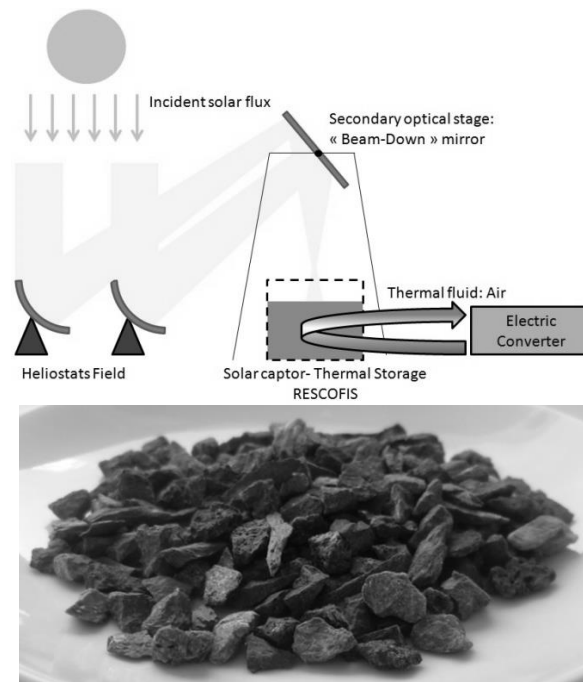


Figure 1. a. General diagram: a “Beam-Down” solar concentrator with an integrated captor/energy storage. b. Piled off COFALIT after crushing and sieving.

Table 1. COFALIT thermal properties between 20 and 1000°C [6]

Density ρ_s ($kg.m^{-3}$)	Heat capacity c_s ($J.kg^{-1}.K^{-1}$)	Thermal conductivity $\lambda_s(W.m^{-1}.K^{-1})$	Thermal expansion coefficient $\alpha(K^{-1})$
3120	800 - 1034	2,1 – 1,4	8,8.10 ⁻⁶

Retaining these technical choice, and considering an annual solar flux similar to Marrakech's, an interior volume of 5 to 55 m³ would be needed for a mirror surface of about 410 to 4100 m², prior to the “Beam-Down” concentrator.

Unstructured porous solar captors are sparsely studied in the literature: the large majority of comparatives are made between structured captors [9, 10]. This work will then not only focus on developing and optimizing an unstructured solar captor, but also to compare it to a more classic structured SiC-based solar captor designed for comparable temperature levels [11].

The main bottlenecks of this project concern the proper design and behavior of all the subsystems, especially for very high temperature levels (expected to range from 600°C in the outlet of the storage compartment to more than 800°C at the center of the captor). Those issues typically include studying the air flow inside all the compartments, maximizing heat exchange while minimizing pressure drop, ensuring the walls can mechanically hold the weight of the granular media, while supporting daily cycles between high and ambient temperature.

The study can be described in three phases:

- Design and optimization of a granular thermal storage: the storage compartment is studied on a small experimental device (interior volume of 0.5 m³), made of piled off rocks that can be compared to COFALIT. The main objective is to fully understand how the thermal storage dynamics depends on the thermal production and consumption for one part, and on the storage thermal and geometric parameters for the other. It is meant to yield to an operational design software. High temperature is not required to conduct such a global study, and as such a range of 100 to 250°C has been chosen.
- Design and optimization of a granular solar captor: the captor compartment is studied on an experimental device made of a COFALIT packed bed, disposed on a small COFALIT thermal storage. This device has been placed under a Xenon arc lamp of 1 kW electric in order to get an estimation of the quality of COFALIT granular bed light absorber efficiency. The objectives are not only the design of a functional granular solar captor, which can maximize energy transfer from the radiative form to the sensible heat form in the heat fluid, but also to compare its performances with those of structured porous solar captors. In order to correctly take into account the radiative part of energy transfer, a temperature level of at least 800°C is required.
- Coupling both parts at a semi-industrial scale, through a 1/10e pilot device: this pilot will be set under a small “Beam-Down” solar concentrator, and will be working under real conditions (true solar irradiance, daily cycles with cloudy skies...). While estimating the global performances of the complete system, this study will also allow to determine the effects of daily cycles on the performances for one part (adapting the regulation to maximize daily efficiency), and on the wall materials for the other

part (cyclic thermal dilatations have to be taken into account in the design of the pilot device). Performances will be estimated on a typical daily cycle, working at required temperature of 600°C in the storage part, and 800° at least in the captor part.

THERMAL STORAGE MODELIZATION

A Simplified Model for a Stratified Thermal Storage

The storage compartment is seen as a subsystem, and is assumed to be an isotropic granular media. The whole model is based on a mesoscopic scale, working on representative volume of control with a size of several grain diameters. The porous media is seen as an equivalent continuous homogeneous media. A transient model is written by combining two sets of equations: the first one describes hydrodynamics in the media, assuming the thermal field is known in both solid and fluid phases. The second one describes energy transfer in the media, assuming hydrodynamics fully known. Combining those two sets can be done though a weak coupling: for a time step small enough, each field can be calculated using the other field as an entry, one time step at a time.

A low velocity range is chosen: a description of hydrodynamics based on a Darcy-Forchheimer simplified model is assumed to be sufficient [12]. Using Darcy velocity in the equations, the relation between pressure drop and velocity in the porous media is given by:

$$\vec{\nabla}P = -\frac{\mu}{K}\vec{u} - \frac{\rho}{K_i}\|\vec{u}\|\cdot\vec{u} \quad (1)$$

Ergun gave the following expressions for the permeability and inertial permeability [13]:

$$K = \frac{d^2 \varepsilon^3}{A(1-\varepsilon)^2} \quad K_i = \frac{d \varepsilon^3}{B(1-\varepsilon)} \quad (2)$$

Constants A = 150 and B = 1.75 are given for spherical particles. Experimental determination must be conducted in order to adapt those constant to an actual media disposed in packed bed.

For low velocity, incompressible flow describes correctly our air flow, and thus the following momentum conservation equation can be written:

$$\nabla \cdot (\rho_f \vec{u}) = 0 \quad (3)$$

A numerical resolution of these equations with a known thermal field yields to a resulting pressure field, and a corresponding velocity field for every point in the storage. Those fields can then be combined with a two-temperature heat equation as follows:

$$\begin{cases} \varepsilon \frac{\partial(\rho_f c_f T_f)}{\partial t} = \lambda_f \nabla^2 T_f - (\vec{u} \cdot \vec{\nabla})(\rho c_f T_f) + h_{vol}(T_s - T_f) & (4a) \\ (1 - \varepsilon) \frac{\partial(\rho_s c_s T_s)}{\partial t} = \lambda_{eq} \nabla^2 T_s + h_{vol}(T_f - T_s) & (4b) \end{cases}$$

Heat exchange coefficient is given by the following correlation [14]:

$$h_{vol} = 700 \left(\frac{\rho_f \|\vec{u}\|}{d} \right)^{0.76} \quad (5)$$

It can be noted here that the effective thermal conductivity in the solid phase λ_{eq} is made of the sum of a purely conductive term, and a radiative contribution term. The conductive term is the mesoscopic scale parameter used to take into account the fluid phase and solid phase thermal properties, as well as local micro-advection phenomena, small deviation from the isotropic hypothesis caused by the directional velocity field, contact thermal resistance between grains... Several models can be found in the literature for describing those phenomena with various porous media and mass flow rates [15, 16, 17]. The radiative contribution is meant to model as an equivalent radiative conductivity the radiant interaction between grains: this equivalent conductivity depends on T_s^3 and is calculated for each time step.

The subsystem physics description is completed by the adjunction of initial conditions and boundary conditions. Considering x the flow direction in the storage and y the transverse direction, boundary conditions in the solid phase can be written as follows:

- The inlet and outlet conditions are assumed to be insulation conditions $\varphi_{in/out} = 0$ in the case of a charge or discharge of the storage. Assuming a zero-flow situation (energy conservation without charging/discharging the device), natural convection will occur on the grid of the system, yielding to the following expression: $\varphi_{in/out} = h_{nat} S_{in/out} (T - T_{ext})$. One should be especially careful when determining the “external temperature” used in this expression, as it reflect in fact the temperature of the steady air in the inlet/outlet conduct (that may be insulated, or may be located near an exhaust pipe...).
- The lateral condition is seen as a thermal loss through a partial contact between the solid phase and the wall: $\varphi_{lat} = G_{eq,s} S (T - T_{ext})$, with $G_{eq,s}$ the equivalent thermal conductance written for the wall with partial contact: $G_{eq,s} = \left(\frac{1}{h_{ext}} + \frac{\theta_{surf} e_{ins}}{\lambda_{ins}} \right)^{-1}$. This conductance takes into account the effective part of the solid grain in contact with the wall θ_{surf} , and the insulating layer properties.

Boundary conditions are written as follows for the fluid phase, when charging/discharging the storage:

- A convective inlet boundary condition with a given imposed temperature: $\varphi_{in} = \dot{m} c_f (T_{in} - T_{ext})$.
- A conductive-convective thermal loss in the lateral direction through the insulated wall, regarding to the surface part of the wall that is not in contact with the solid phase :

$\varphi_{lat} = G_{eq,f} S (T - T_{ext})$, with $G_{eq,s}$ the equivalent thermal conductance written for the wall with partial solid/solid contact:

$$G_{eq,f} = \left(\frac{1}{h_{ext}} + \frac{(1-\theta_{surf})e_{ins}}{\lambda_{ins}} + \frac{(1-\theta_{surf})}{h_{int}} \right)^{-1}.$$

- A “free-flow” convective condition is assumed on the outlet: $\varphi_{out} = \rho c_f u(x, y)(T(x, y) - T_{ext})$. Coupling the mass conservation with the energy conservation is required in order to use this non-homogeneous outlet condition: the main fluid trajectories are highly dependent of the structure of the porous media (enclosure, local porosity field ...).

A combined iterative resolution for those two modules (velocity field and temperature field) allows to completely describe the full system dynamics, and can yield to comparative studies between materials that can be used in the packed bed storage. Resolutions can also be made concerning storage volume, charging and discharging power, velocity range, and other practical choices concerning design or regulation parameters.

This simplified model should then be validated. The validation process will imply the use of a dedicated experimental bench, as described in paragraph 2.2. But this model can only be used assuming several parameters related to the porous media are known: the porosity field in the bed is of particular interest, as well as thermal properties (conductivity, heat capacity) for the solid and fluid phases, density of each phase, size distribution of the grains, average emissivity of the solid phase in the working temperature range, fluid viscosity, and finally an order of magnitude of those parameters variations with temperature. Literature can help finding these values, but the use of an unstructured granular material, with non-spherical grain made of a not well-known material may require an experimental identification of several parameters (COFALIT is a product made of melted waste: its composition, thermal and optic properties may vary a little from one batch to another). Using a modified least square criteria minimization together with a dedicated experimental device may be appropriate (depending on the desired parameters, a modified least square with a Bayesian approach has been used in our experiments, with a relaxation factor in order to ensure the convergence. See Testu for a detailed example [18]).

Using a first set of experiments allow us to identify all the missing parameters specific to that experimental device/porous medium. A validation can then be implemented on a second set of experiments, realized on the same device. That work has been realized but will not be presented in this paper, as a later dedicated paper will focus on this particular study.

Experimental Protocol for the Model Validation on a Dedicated Thermal Storage Device

The experimental device used to perform parameters estimation is represented on Figure 2. The porous media is enclosed between two metal grids on the inlet and outlet boundaries, and four insulated walls (made of high density rock wool, considering the relatively low temperature level). Considering the steel-based external envelop, refractory support are used to maintain both grid in place while avoiding thermal bridges. A 0.5 m³ interior volume is used to dispose the granular media. An average porosity of 0.4 is obtained by manually stacking and packing the grains. Those grains were produced by crushing of melted waste, and thus are not spherical, but can be approximated as such with an equivalent diameter of

about 1 cm. Instead of COFALIT, a limestone rock-type was tested here: thermal properties may vary a bit, but observed phenomena concerning the storage dynamics will still allow to estimate the media parameters and then to build up an optimization software. A horizontal air flow is implemented: in order to avoid a preferential flow near the surface of the porous media, a flexible insulated wall is used above the media.

While a solar power source was available, most tests used a gas power source (propane burner) to ensure both a constant inlet temperature and a constant inlet power, yielding to a stable air flowrate for a period of a day. A 100 to 250°C inlet temperature was required, which allows to work with a large range of flowrate (from 10 to 130 kg.h⁻¹) during 5 to 10 hours. Thermal powers were about 4 to 6 kW in charge and discharge.

Discharging the storage can be realized by inverting the fluid circulation: ambient air is used to extract the energy from the storage, and is then transported to a heat exchanger to evacuate that energy without impacting the solar part of the system.

Every test is followed through the use of 25 K-type thermocouples (8 thermocouples in the axial direction, and 2 orthogonal measurement planes made of respectively 13 and 4 lateral thermocouples, added to the corresponding axial one).

Considering the chosen average diameter of the grains and flowrate range, fluid and solid phases temperatures can be considered to be in a thermal quasi-equilibrium: that equilibrium temperature is measured by the thermocouples, located at the surface of the grains. A Pitot tube static anemometer gives a measure of the air flowrate.

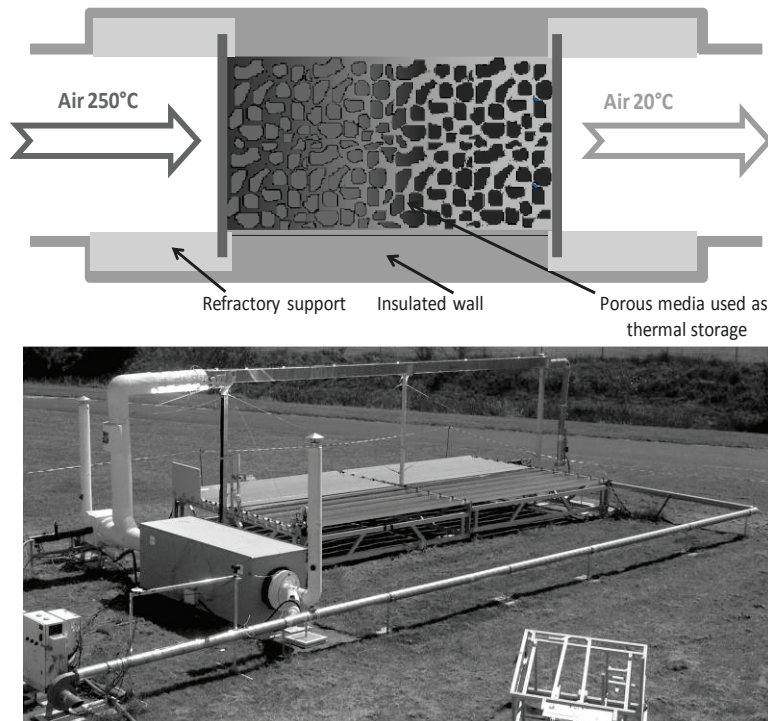


Figure 2. a. Thermal storage simplified representation. b. Dedicated thermal storage coupled with a Linear Fresnel Mirror power plant of 7 kW (average on a sunny day, a stable gas power source is also available).

Three kinds of test were performed using this device:

- Constant inlet temperature and flow charges.
- Estimation of a fully charged and half charged storage performance for energy conservation. Measurements were realized near the walls and at the center of the media.
- Constant inlet and flow discharges, either directly after charging or after a 15-hour wait.

Thermal Storage: Results and Discussion

Static and dynamic experiments were conducted (charge and discharge with constant inlet temperature and flowrate, monitored wait period on a fully-charged or half-charged storage to quantify thermal loss). An example of a charge using a gas power source is shown on Figure 3: a high flowrate was used with a constant inlet temperature of 135°C in spite of a low solar resource. Lateral thermocouples have been used in those experiments, but are not represented on Figure 3.

This charge was combined to a multidirectional model to take into account the stratified side of this storage: thermal exchange between solid and fluid phases is quite efficient, and thus a thermal front was progressing in the flow direction during the charge, forming what is called a thermocline. Thermal dispersion caused by local microscopic phenomena and effective conductivity yielded to a spreading of the front with length. In addition, measurements showed the importance of porosity on the temperature field, and its impact on preferential direction for the air flow. Those preferred paths were caused by an inhomogeneous packing when the bed was constructed. Considering the chosen mean grain diameter, heat exchange between solid and fluid phases were found to be very efficient with that flowrate range, and thus the heat exchange coefficient has not been precisely identified: the sensitivity of the thermal field to this parameter was low.

Figure 4 shows that our model allows us to simulate charge and discharge operations for a given storage design, with a selected constant flowrate and inlet temperature, and a chosen solid material. Observing the outlet temperature through time, a gap of temperature between charge and discharge can be seen on both boundaries of the storage. Those gaps are a key parameter in designing and optimizing a thermal storage in volume, depending on the desired outlet temperature and the required thermal power while discharging. They can be interpreted as a measurement of the recoverable energy, and depends on the chosen geometry, materials and regulation.

Several static experiments were performed on the experimental device: the effective thermal conductivity of the media was determined without airflow. Heat exchange coefficients on the wall were estimated as well, and it has been noted that for a 15-hour wait period after a charge, natural convection does not occur in the media. The temperature field was only deformed through effective conduction, mainly in the axial direction. The media was cooled by convection at the boundaries, on the grid. Considering that several thermal bridges were still in existence, a bias has been noted while estimating the system performances: further tests will have to be realized to correctly estimate the energy conservation efficiency.

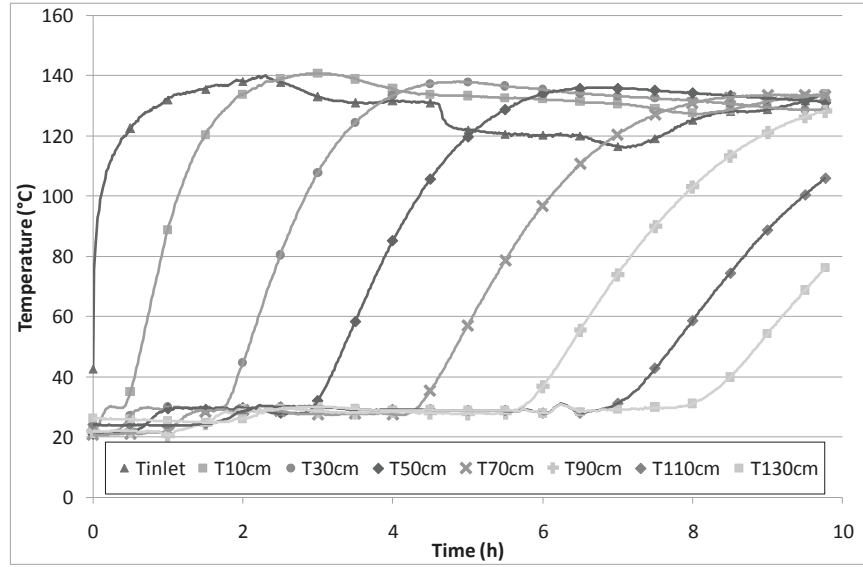


Figure 3. Experimental measurements for a 135°C charge: axial measurements over time.

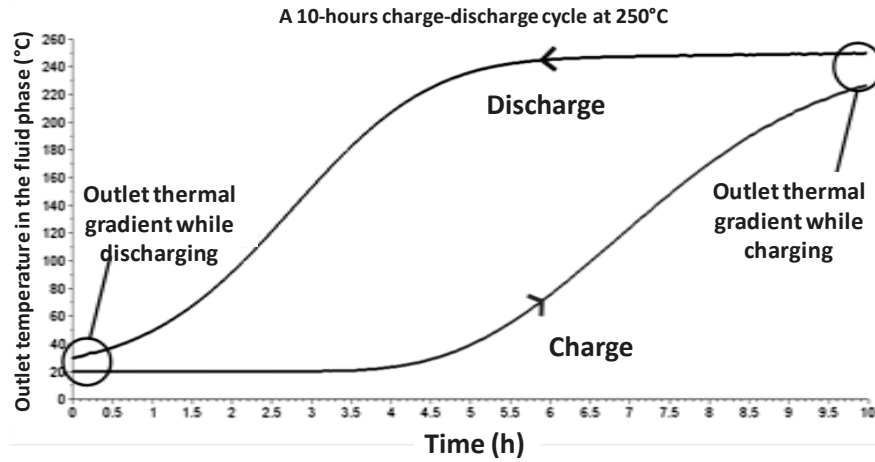


Figure 4. Simulation of a charge – discharge cycle: outlet temperatures.

These experimental results allow us to validate our model, and yielded to the determination of several experimental parameters highly dependent of our porous solid material. This model can then be used together with a solar production profile and a desired energy need profile in order to predict precisely the thermal state of a given storage device, hour by hour. An estimation of the total thermal losses can be made over a year, as well as a precise outlet temperature profile for every hour of discharge. This temperature level can then be linked to the electric converter yield (degrading the fluid temperature will have a negative impact on the converter yield, yielding to additional energy losses in the conversion process). Comparing those energy losses with the thermal losses previously obtained, an optimum can then be reached for the storage device (volume, dimensions, solid material, porosity ...). Each

optimum is specific to a given solar production profile and energy need profile. These optimizations are still in development and will be detailed in further works.

THE UNSTRUCTURED SOLAR CAPTOR DESIGN

Description of a High-Temperature Packed Bed System

An unstructured packed bed solar captor can be modeled as a porous granular media: hydrodynamics and heat exchange of such a system can still be described through equation (1) to (5). Particular attention has to be paid to the radiant component of thermal exchange, as very high temperature levels can be locally obtained (a 1200°C local temperature may be possible at the focus point of the concentrated solar beam).

Meshing the bed, choosing a method to solve those equations, and then deciding on a time step, space step or boundaries conditions highly depends on geometry. The most important boundary condition concerns the enlightened surface at the top of the bed: it must be assumed that the space step used to describe physics on this surface is about the same order of magnitude that the thickness of the selective layer, about 1 to 2 grain diameters. Equation 4b can then be written considering this thickness e :

$$(1 - \varepsilon) \frac{\partial(\rho_s c_s T_s)}{\partial t} = \lambda_{eq} \nabla^2 T_s + h_{vol}(T_f - T_s) + a \frac{\phi_l}{e} - p \frac{\varepsilon \sigma}{e} (T_s^4 - T_{ext}^4) \quad (6)$$

In this equation, a is the mean absorption factor of the selective layer, calculated for the whole solar spectrum, and p is a macroscopic form factor used to ponder the emission part of the energy out of the captor. The solar captor is built as a cavity, and depending on the geometry, only a small part of the emitted energy on the selective layer will effectively come out of the captor. Complex series of reflections occur inside the cavity yielding to the emitted energy heating the wall inside the cavity. Those heated walls contribute to reduce the emitted loss of the packed bed for one part, and may be cooled by the airflow to minimize total energy loss for the other part. This p factor highly depends on the geometry and materials used in the design of the captor.

The main objective of the study is to maximize this subsystem performance by adapting geometry (that affect radiant energy transfer in the captor cavity and in the porous media, and the fluid flow) and choosing several solid materials (which directly impact parameters such as the absorption factor, inertia, effective conductivity and thermal dispersion, high temperature behavior, grain diameters ...). An experimental identification for those parameters will have to be realized.

Description of the Experimental Device Dedicated to the Solar Captor Study

The dedicated experimental device used in characterization and optimization of the solar captor is represented on Figure 5. Two compartments are disposed one above the other: the first one includes both the cavity solar captor and the granular porous media that contain the selective layer, while the second one is a small-size thermal storage for safety purpose.

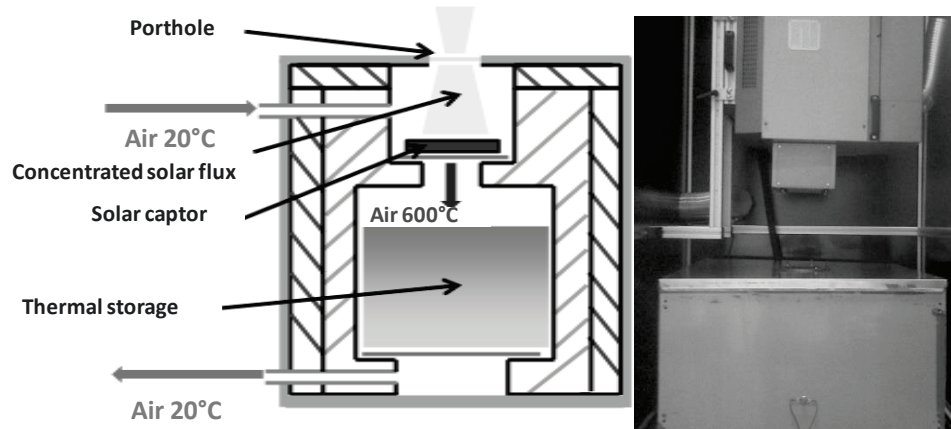


Figure 5. a. A simplified representation of the solar captor characterization device.
b. Photography of the solar captor device under its artificial sun.

A highly-concentrating Xenon arc lamp is used as an artificial sun: it delivers a 850 W light beam at the focal spot. A solar-type light spectrum is assumed on this kind of solar lamp. By settling the relative height of the lamp, it is possible to adjust the spot diameter on the selective layer from 5 to 15 cm.

The safety storage is a 30-centimeters high cube, filled with a porous media constituted of COFALIT grains. The selected grain diameter is about 3 cm. Instrumentation has been sparsely implemented in the storage with only 4 axial and 4 lateral K-type thermocouples. The objective is essentially to protect exhaust canalizations from high-temperature airflow. Secondary objectives for this storage include validating energy conservation, detecting potential air leaks, and confirming results that were obtained thanks to the low-temperature study.

The solar captor compartment includes a modular cavity. Several porous media can be tested, for a maximal volume equal to a 15-cm high cube. Different geometries can be tested inside this cavity, by reducing the porous volume and completing with insulated materials, such as insulated light bricks. Two kinds of porous media were tested: insulated media mainly constituted of piled off COFALIT grains, and more conductive solid materials, disposed in packed bed. Three available grain diameters were used: 5, 7.5 and 10 cm.

A quartz-made porthole is used as cavity ceiling: it allows a very low air leak rate, a quasi-total transmission of the light to the captor, and can be easily manipulated between tests to change the cavity geometry.

A multilayer thermally insulated wall is used: the interior layer is made of high-temperature resistant insulated light bricks, which were needed in order to support the porous media while standing the high temperature level of the storage ($>600^{\circ}\text{C}$). The external layer is made of high-density rock wool, which presents a better insulating power than bricks but will start losing its thermal properties above 400°C .

Flowrate is measured in the inlet of the system through the use of a hot wire anemometer (outlet measurements can be realized between tests with a cold circulating airflow). The solar captor instrumentation includes 15 T-type thermocouples (9 in axial position and 6 in lateral position). Axial and lateral thermal dispersion are followed throughout an experiment, and the study of thermal gradient in the packed bed allows to quantify heat exchange efficiency

between solid and fluid phase, in order to optimize performances. Because of the great complexity of modeling the chosen conductive matrixes used here, those measurements have been used to estimate average exchange coefficients and equivalent conductivities through experimental inversion methods. It can be noted that thermocouples are protected with a refractory stainless steel jacket, which can support high-temperature levels (up to 800°C). For high irradiance concentration rates however, the jackets cannot support the temperature at the center of the focal spot, which can exceed 1200°C. In addition, the reflective comportment of these jackets prevents us to use it to measure precisely the surface temperature: the highest thermocouple is placed for a 2.5 cm depth from the surface.

Solar Captor Experimental Device: Results and Discussion

A first series of tests resulted in heating air from 20°C to 200 - 250°C for several operational conditions: pure COFALIT solid matrixes were tested, as well as more complex conductive matrixes. Several focal spot diameters were tested on the selective layer, for a total incident radiant power of 850W. Figure 5 shows the steady states that were reached for two of those tests.

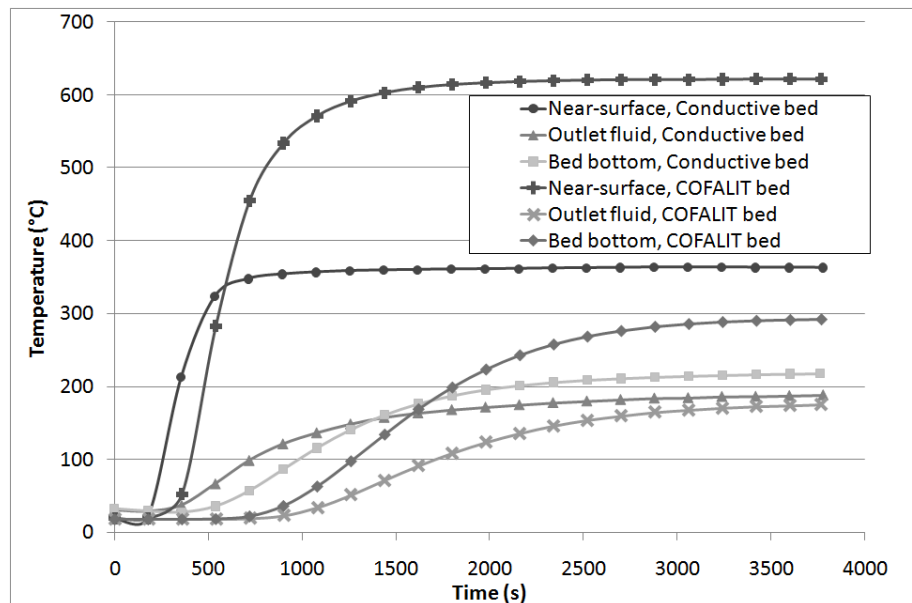


Figure 6. Variation of temperatures with time (solid near the surface, solid at the bottom of the receptor matrix, and fluid temperatures) for two different porous media (pure COFALIT and Conductive matrix) and 2 different flow rates.

Figure 6 shows that a conductive granular media yields to very close solid and fluid temperatures at the bottom of the packed bed. Such a porous media would allow to design an optimized solar captor with a low thickness, providing both high heat exchange efficiency and good volumetric thermal dispersion of the energy. In the case of a pure-COFALIT granular media, such a thermal equilibrium between solid and fluid phases is not reached at the bottom of the bed. It can be noted that different flow rates were used in those tests. Both tests were

realized with a 5-centimeters wide focal spot, and yielded for about the same fluid outlet temperature: in the COFALIT experiment, thermal dispersion was inefficient and a lower flowrate was obtained than in the conductive media experiment. The remaining energy was emitted on the surface, with higher solid temperature obtained for the COFALIT test.

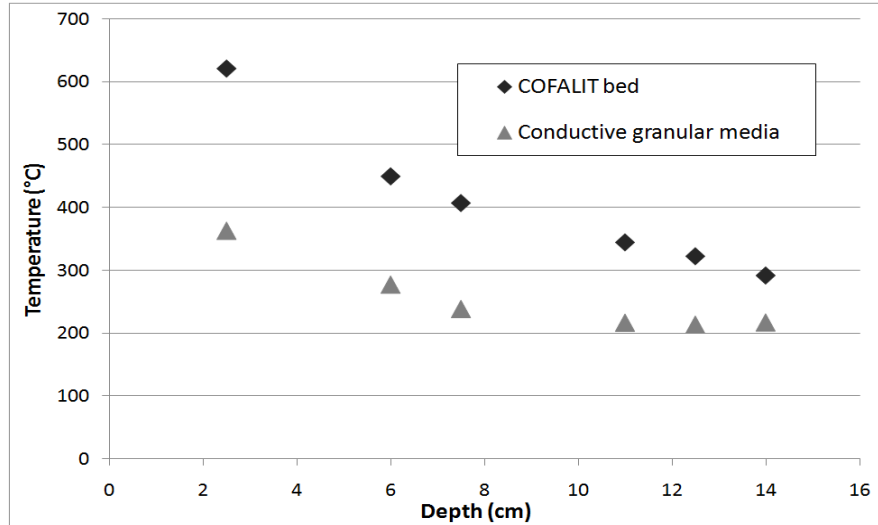


Figure 7. Steady state measured axial thermal field for two porous media (pure COFALIT and Conductive matrix) using the same operating conditions (spot diameter at the surface, flowrate).

Minimizing the thermal gradient between surface and bottom of the packed bed is then required to maximize thermal efficiency: although in a granular media, conduction occurs by the mean of contact points only, Figure 7 shows that equivalent conductivity of the granular media is the key factor for reducing that gradient, and thus minimizing emitted energy at the surface.

Several test series were conducted on this device, and yielded to an optimized geometry, the choice of a efficient granular media, and a method to select air flowrate in order to produce air at a 450°C temperature, for a constant light power. Some geometry upgrade will be done in further studies to improve heat exchange between phases and reduce the emitted part of the energy on the selective layer.

SCALING UP TO THE SEMI-INDUSTRIAL SCALE: DESIGN OF A 1/10TH PILOT DEVICE

The Pilot Power Source: A Small Size “Beam-Down” Solar Concentrator

Experiments on a semi-industrial pilot device will be realized in order to valid several points: coupling of both subsystems, understanding and modeling of that global system under true solar conditions (full sunny day, clouds ...). Moreover, a 1/10e sized pilot will yield to the estimation of the coupled performances with minimum wall effects.

Concerning that particular point, minimizing wall effects requires a large thermal storage volume: in order to make some tests on a daily basis, a high solar power is required. The corresponding dedicated solar concentrator will be a small-size “Beam-Down” concentrator, which will constitute one of the first devices of that kind available to Research and Development. Considering a several dozen square meters mirror surface for the first optical stage of that prototype, a 10 to 20 kW maximum power would then be reached.

Furthermore, that “Beam-Down” concentrator will be useful even without the coupled solar captor/thermal storage unit; it can indeed yield to:

- Models validation concerning the focal spot size and form over a day/a year.
- Estimations of its optical performances.
- A 2-axis high precision solar tracking conception and test.
- The secondary mirror stage precise design.
- A safety study about the global system through defocusing of the heliostat in case of danger.

All those points are much needed to develop the whole “Beam-Down” sector further: that technology allow to reach an interesting compromise between power and fluid temperature, and should be competitive against classical one-reflection system (parabolic trough) and two-reflection system (solar tower). Solar concentrator of the “Beam-Down” type should also be easier to design and maintenance should be facilitated: a validation of that point will be done on this installation.

Mechanical Studies Concerning Wall Resistance over Thermal Cycles

Tests conducted on a full system pilot device offer the opportunity to valid wall design, concerning wall resistance to mechanical and thermal phenomena for high temperature daily cycles. Storage wall are indeed made of insulated porous bricks, which are thermally resistant but not particularly mechanically resistant; a thermal cycle, with both a charge and a discharge in the storage unit, will cause the wall to see an intern temperature varying from 20°C to more than 600°C. During thermal cycles, the walls are subjected to differential thermal dilatations, and enhanced mechanical constraints as detailed below. The objective is to be able to keep at a minimum the air leak rate, even after several years of daily solar cycles.

Those walls are made of thermal bricks, linked by refractory cement: differential dilatations occur when heated. On the inside, thermal dilatation of the packed bed will yield to an increase of mechanical constraints on the wall [19, 20]. A simplified modeling using a Janssen approach in the bed coupled to a finite elements calculation in the bricks allowed to consider this mechanical effect in the pilot design phase. Corresponding technical choices were made (geometry for the hot and cool area of the global system, assembling method of the captor and storage subsystems, wall construction methods, storage dimensions...). An experimental validation is still required in order to scale up to industrial scale.

Some Points That Still Need to Be Studied on the Pilot Device

The 1/10th pilot device offer a way to study the following points:

- Control and regulation of a coupled solar captor/thermal storage in variable solar conditions over a day, charging and discharging the storage unit in order to produce with a constant power, or with a variable required power if needed.
- Estimation of the full system performances, either maximum performances or averaged one over a day. Wall effects can only be neglected with a storage volume high enough: laboratory studies on small experimental device cannot truly approach this.
- Characterization of eroding phenomena, both for the walls and the granular media, due to dilatation effects during thermal cycles. Fine particles production is expected to occur during the first dozen of thermal cycles. Changes in the arrangement of the grains could also happen, impacting constraints on the wall and grains. Precise effect on wall durability is still unknown.

CONCLUSION

A compact coupled system including a solar captor and a thermal storage has been presented. This system is meant to be used together with a solar concentrator of the “Beam-Down” type, and is based on packed bed filled with high-performances low-cost granular media. One of those granular materials is COFALIT, a product made of asbestos-based melted waste. Air is the selected heat fluid, allowing to work with high temperature levels.

Laboratory studies for both the solar captor subsystem and the thermal storage subsystem were presented. The captor corresponding device is coupled to a 850 W Xenon arc lamp and allow a 800°C temperature on the selective layer at the focal spot. The thermal storage corresponding device is powered by a 4 to 6 kW solar source, coupled to a gas burner in order to ensure a constant power source if needed. Air with a 200 to 250°C temperature is used to study charge/discharge cycles. Objectives of those preliminary studies include key parameters identification, control and regulation of those subsystems, performances and limits estimations, and finally technical choice concerning material and geometry in order to optimize a global system. Consequently, effective conductivity of the captor part was found to be a key parameter in increasing the volumetric efficiency of heat exchange. Enhancing this parameter through the use of highly conductive granular matrixes has been proved to be an effective way to increase the captor global performances. A 475°C fluid temperature has been reached in those studies.

Stakes of a future 1/10th semi-industrial pilot were presented. This device includes a “Beam-Down” solar concentrator using a several-dozen-square-meters mirror surface. Additional studies are still required before finally designing the pilot device.

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