Structural Design of Parabolic-Trough Solar Concentrators

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SUMMARY. A new research devoted to the design of parabolic-trough systems for solar power plants is here described, as well as the most recent innovations in terms of modeling heat storage concrete tanks for molten salts are reported.

1 INTRODUCTION

A new generation of power plants, with concentrating solar power systems, uses the sun as a heat source. There are three main types of concentrating solar power systems: parabolic-trough, dish/engine, and power tower. All of these rely on the same basic principle, in which light is concentrated to a central receiver using mirrors or refractive optics. Concentrators require direct solar illumination, and the optics or mirrors must move during the course of the day to track the sun’s trajectory. A key benefit of concentrator devices is in reducing the physical size of the receiver relative to the area in which the light is gathered.

A power tower system uses a large field of mirrors to concentrate sunlight onto the top of a tower, where a receiver sits. This heats molten salt flowing through the receiver. Then, the salt's heat is used to generate electricity through a conventional steam generator. Molten salt retains heat efficiently, so it can be stored for days before being converted into electricity. That means electricity can be produced on cloudy days or even several hours after sunset. A dish/engine system uses a mirrored dish (similar to a very large satellite dish). The dish-shaped surface collects and concentrates the sun's heat onto a receiver, which absorbs the heat and transfers it to fluid within the engine. The heat causes the fluid to expand against a piston or turbine to produce mechanical power. The mechanical power is then used to run a generator or alternator to produce electricity. Parabolic-trough systems concentrate the sun's energy through long rectangular, curved (U-shaped) mirrors. The mirrors are tilted toward the sun, focusing sunlight on a pipe that runs down the center of the trough. This heats the oil –generally used, but ours is not the case- flowing through the pipe. The hot oil then is used to boil water in a conventional steam generator to produce electricity.

Our research is devoted to the last type of technology. Particularly ENEA, on the basis of the Italian law No. 388/2000, has started an R&D program addressed to the development of CSP concentrated solar power systems able to take advantage of solar energy as heat source at high temperature. One of the most relevant objectives of this research program [1] is the study of CSP systems operating in the field of medium temperatures (about 550°C), directed toward the development of a new and low-cost technology to concentrate the direct radiation and efficiently convert solar energy into high temperature heat. The current innovative ENEA conception aims to introduce a set of innovations, concerning: (i) The parabolic-trough solar collector, an innovative design to reduce production costs, installation and maintenance and to improve thermal efficiency is defined in collaboration with some Italian industries; (ii) The heat transfer fluid: the synthetic hydrocarbon oil, which is flammable, expensive, and unusable beyond 400°C, is substituted by a mixture of molten salts (sodium and potassium nitrate), widely used in the industrial field and chemically stable up to 600°C, and (iii) The thermal storage: it allows the storage of solar energy, which is then used when energy is not directly available from the sun (night and covered sky). The double aboveground tank system is generally the more common solution for heat thermal storage in a solar plant, requiring very big tanks, having a height of about 12 meters, a diameter greater than 20 metres and a cost for the steel liner equal to half of the total cost is reached. ENEA was interested to explore the SERI solution [2], Figure 1, proposing a below-grade cone shape concrete tank, which appears to be at a lower cost and a safer one, but substituting the 900°C molten carbonate salts with a more stable mixture.

The research activities in collaboration with ENEA (still ongoing within the Elioslab Project) have allowed to: a) identify the constitutive models of concrete by means of coupled chemo-hygro-thermo-mechanical analyses; b) evaluate heat and mass transfer in concrete and evaluate damage under prolonged thermal loads [3]; c) estimate the tank seismic behaviour and d) propose an innovative design for the solar-trough collectors to reduce production costs [4]. The thermo-mechanical performances of the steel liner (keeping the molten salts from coming into contact with any other part of the tank) are being studied in this period.

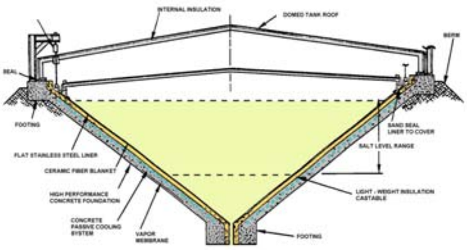


Figure 1: Below-grade conical tank, as proposed in [2].

2 DESCRIPTION OF PARABOLIC-TROUGH SOLAR CONCENTRATORS

The parabolic-trough solar concentrators are one of the basic elements of a concentrating solar power plant. The functional thermodynamic process of a solar plant is shown in [5]. The main elements of the plant are: the solar field, the storage system, the steam generator and the auxiliary systems for starting and controlling the plant. The solar field is the heart of the plant; the solar radiation replaces the fuel in conventional plants and the solar concentrators absorb and concentrate it. The field is made up of several collector elements composed in series to create the single collector line. The collected thermal energy is determined by the total number of collector elements which are characterized by a reflecting parabolic section (the concentrator), collecting and continuously concentrating the direct solar radiation by means of a sun-tracking control system to a linear receiver located on the focus of the parabolas. A circulating fluid flows inside a linear receiver to transport the absorbed heat. A solar parabolic-trough collector line is divided into two parts from a central pylon supporting the hydraulic drive system [6]. Each part is composed by an equal number of identical collector elements, connected mechanically in series. Each collector element consists of a support structure for the reflecting surfaces, the parabolic mirrors, the receiver line and the pylons connecting the whole system to a solid foundation by means of anchor bolts. The configuration of a solar parabolic-trough collector is that of a cylindrical-parabolic reflecting surface with a receiver tube co-axial with the focus-line, as a first approximation. The reflecting surface must be able to rotate around an axis parallel to the receiver tube, to constantly ensure that the incident radiation and the plane containing the parabolic sections axles are parallel. In this way the incident solar light on the reflecting surfaces is concentrated and continuously intercepted by the receiver tube in any assumed position of the sun during its apparent motion. The parabolic-trough collector is then constituted by a rotating "mobile part" to orientate the concentrator reflecting surfaces and by a "fixed part" guaranteeing support and connection to the ground of the mobile part.

The solar collector performances, in terms both of mechanical strength and optical precision, are related to one side to the structural stiffness and on the other to the applied loading level. The main load for a solar collector is that coming from the wind action on the structure and it is applied as a pressure distributed on the collector surfaces. From a structural point of view, it must be emphasized that the parabolic-trough concentrator is composed mainly by three systems: the concentration, the torque and the support system. Other fundamental elements, not treated in this paper for sake of brevity, are the foundation and the motion systems. All elements should be considered when designing a parabolic-trough concentrator and verified for "operational" and "survival" load conditions. Corrosion risks and safe-life (about 25-30 years) must be taken into account. The following basic operational conditions, listed in Table 1, can be considered valid for a parabolic-trough concentrator; they define different performance levels under wind conditions. "Design conditions" can be fixed consequently.

Table 1: Operational conditions

Level	***Condition***
W1	Response under normal operational conditions with light winds. The concentration efficiency must be as high as possible under wind velocity less than a value v_1 characterizing this level.
W2	Response under normal operational conditions with medium winds. The concentration efficiency is gradually diminishing under wind velocity comprised between v_1 and v_2. The wind velocity v_2 characterizes this level.
W3	Transition between normal operating conditions and survival positions under medium-to-strong or strong winds. The survival must be ensured in any position under medium–strong winds. The drive must be able to take the collector to safe positions for any wind velocity comprised between v_2 and v_3. The wind velocity v_3 characterizes this level.
W4	Survival under strong winds in "rest" positions. The survival wind velocity must be adapted to the requests of the site according to recommendations. The wind velocity v_4 characterizes this level.

Finally, on the basis of what described above, the main requirements when designing a parabolic-trough concentrator can be summarized as follows:

• Safety: the collector structures exposed to static loads must guarantee adequate safety levels to ensure public protection, according to the Italian Law 1086/71. This is translated into a suitable strength level or more generally in safety factors for the construction within the Limit State Analysis.

• Optical performance: the structure must guarantee a suitable stiffness in order to obtain, under operational conditions, limited displacements and rotations, the optical performance level being related to the capacity of the mirrors concentrating the reflected radiation on the receiver tube.

• Mechanical functionality: the structural adaptation to loads must not produce interference among

mobile and fixed parts of the structure under certain load conditions.
• Low cost: the structure has to respond to typical economic requirements for solar plant fields (e.g. known from experiences abroad): unlimited plant costs lead to non-competitive sources employments. This can lead to tolerate fixed damage levels of the structure under extreme conditions (i.e. collapse of not-bearing elements, local yielding, etc.), but still respecting the above mentioned requirements of public protection.

3 CODES OF PRACTICE AND RULES

The parabolic-trough concentrator, on the basis of its structural shape and use and further considering available national and European recommendations, is classifiable as a “special structure” [4]: it is not a machine or a standard construction. The definition “special” comes directly from a subdivision in classes and categories according to the criterion of the “Rates for professional services” as it results from the Italian law n. 143/1949; this law places “Metallic structures of special type, notable constructive importance and requiring ad-hoc calculations” into class IX e subclass b. From the functional analysis of the structure its special typology clearly emerges, according to its design, technical arrangements and innovation. When the parabolas are stopped in an assigned angular configuration, the nature of the structure can be determined: steel structure of mixed type founded on simple or reinforced concrete placed on a foundation soil having characteristics closely correlated to a chosen site, also under the seismic profile. From the structural point of view the dynamic characteristics play a major role, with the response deeply influenced not only by the drive-induced oscillations, but also by dominant winds or seismic actions. Taking into account the above considerations, it is then possible to state that the examined structure is “special”. Moreover, such a structure requires appropriate calculations since some parts are mobile, even if with a slow rotation; at the same time the structure is subjected to wind actions, especially relevant due to the parabolas dimension. The simultaneous thermal and seismic actions, acting as self-equilibrated stresses in an externally statically indeterminable structure, are equally important. Special steel made structures are e.g. cranes: they are designed using specific recommendations; in our case the reference to existing codes of practice is necessary, even if with the aim of adapting them and/or proposing new ones for CSP systems. Hence it clearly appears that such structures, built within the European countries, are currently designed and verified out of standards; the only two Italian recommendations acting as guidelines are:
• Law 5/11/71, n.1086, Norms to discipline the structures made by plain and pre-stressed reinforced concrete and by metallic materials.
• Law 2/2/74, n.64, Procedures devoted to structures with special prescriptions for seismic zones.

Again, several “technical norms” are related to the above ones, in form of “Minister (of Public Works) Decree”, or “explanation documents”, or other documents giving rise to a certain amount of duplications and repetitions; however, a progressive compulsory use of Eurocodes is being introduced to push Italian engineers more properly into the European environment. In this case, Eurocodes 3 and 8 are of interest for the structural design of solar concentrators, also in view of their seismic performance. It is important to make an advanced choice regarding the body of recommendations to be followed in the design and checking phases and to proceed further with them, avoiding the common mistake of some designers to take parts from one norm (i.e. Italian) and mix it with parts of another norm (i.e. Eurocodes). The main problems in the so-called harmonization of rules within Europe reside in finding safety coefficients to be applied for considering special conditions (e.g. environmental) in each country, as well as those for materials.

This is a source of difficulty in the creation of a unique body of rules valid in the whole European territory. The last product of recommendations recently emitted by the actual Ministry of Public Works in Italy is a 438 pages document (plus two Annexes) named "Testo Unico per le Costruzioni". It is compulsory in the Italian territory from July 1st 2009. The aim of this decree was also to unify a series of previous decrees into a single document. As already stated, it has been here chosen to follow the current Italian Laws, and Eurocodes for comparison, in view of the possible application of solar concentrators at Priolo (near Syracuse, Sicily). In principle, with a few changes, it is possible to apply the technology in other sites, as well as outside Italy or even Europe: slight changes in dimensioning could occur.

4 LOADS

Given the design loads, subdivided in permanent and variable ones, wind conditions have been examined more in detail, whose effects on the structure are connected to the parabolas aerodynamics in their different characteristic positions (see below). The role of the snow and of other possible variable loads coming from thermal actions or differential settlements at foundations level has been additionally considered. In the following wind loads only will be examined for brevity.

4.1 *Wind action on the parabolas*

The solar concentrator shape is taken into account by means of aerodynamic coefficients. The different aerodynamic shape coefficients have been identified by means of a CFD analysis carried out in [7]. These coefficients have been determined starting from wind actions exerted on the linear parabolic collector as functions of its angular position (Figure 2). Such coefficients have been calculated for the most (external) and the least (internal) stressed collectors. An external collector is one of those belonging to the first line without any artificial barrier against wind actions, whereas an internal collector is one on the sixth line, taken as representative of all the others.

Full tables for shape coefficients in case of “external” parabolas as well as “internal” ones are reported in [8] and used in [9] for structural assessment within the Limit State Design. Shape coefficients have been used to evaluate drag (C_{fx}), lift (C_{fy}), torsion (C_{Mz}) and mean pressure (C_{pm}), each of them being function of the concentrator rotation angle, where the allowed rotation is in the range +/- 120°. Then, shape coefficients for mean pressures have been calculated as functions of the aperture angle for “external” or “internal” parabolas. By analyzing the above coefficients it is possible to identify the parabolas’ characteristic positions listed in Table 2.

Observing Figure 3, it comes out clearly that aerodynamic coefficients and associated loads are largely reduced at the internal collectors. The main reason resides in the shielding effect produced by the first collectors rows. This remark leads to the necessity of designing “strong” collectors along the external rows and “light” collectors along the internal ones. Alternatively, it is possible to choose a different design strategy, based on the introduction of opportune windbreak barriers and on the realization of “light” collectors only. The position characterized by smaller loads is at 180°. This is only a theoretical, unattainable position because of the interferences between receivers and pylons. The safety position to be really taken in consideration is at about -120°. The waiting position (at 0°) does not guarantee an adequate level of protection for the mirrors. All the positions shown in Table 2 must be taken into account during the design phase but the most relevant position is, without doubt, the one associated to the maximum torque action. This is consequence of the fact that torque effects are accumulated along all the line, producing the maximum stresses on the structural elements close to the central pylon. This can be considered the key action in the parabolic-trough solar concentrators wind design.

5 GLOBAL AND LOCAL VERIFICATIONS

5.1 *Load combinations*

Particularly, the “Semi-Probabilistic Limit State Analysis” has been chosen in our design process, where “limit state” is a set of performance criteria (e.g. vibration levels, deflection, strength), stability (buckling, twisting, collapse) which must be met when the structure is subjected to loads. The limit state design requires the structure to satisfy two main criteria: the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS); the former refers to structural collapse or other forms of structural failure, being differentiated into three main states: elastic, plastic and stability LS; the latter is evidenced when specified service requirements are no longer met (e.g. performance of constructions –or parts of them-, comfort for people, appearance), differentiated into: LS for excess of deformation, LS for excess of vibration, fatigue LS.

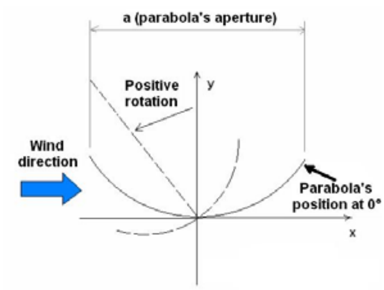


Figure 2: Parabolic concentrator scheme at different angular positions.

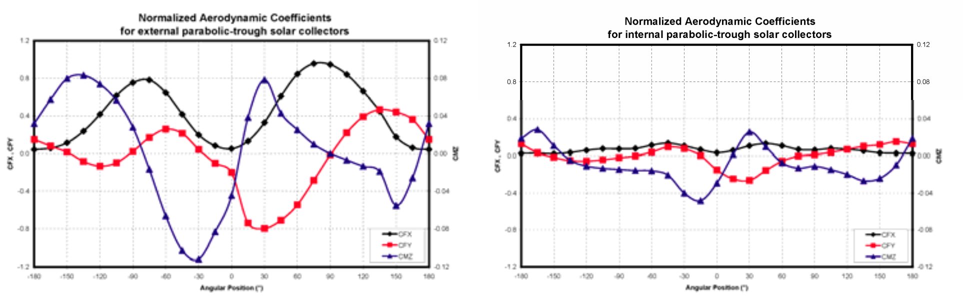


Figure 3: Angular distribution of the normalized shape coefficients for “external” (left) and “internal” (right) parabolas.

Then, to take into account the specificity of the investigated structures, it was necessary to combine together operational states (OSs) [4], characteristic positions and load actions, reaching to the interpretation of Table 3 within the context of a limit state analysis [5].

It is to be noticed that the characteristic position corresponding to 120°C has been excluded from the verifications being technically unreachable if a correct parabolic collector functioning is to be hypothesized. Additionally, within the SLSs the conditions of maximum rotation (W_1 operational state) and maximum deformation (W_2) must be verified; W_3 requires the collector operability within an elastic ULS, i.e. absence of permanent deformations. Differently, such deformations can be present within W_4 but without leading to a structural collapse.

In the following some design features for the concentration system are described.

Table 2. Wind effect: characteristic positions

Characteristic Effect	**Angular position (degrees)**	
	“External” collector	**“Internal” collector**
Safety position	-120	-120
Waiting position	0	0
Maximum torque effect	-30	-15
Maximum bending action on the torque tube	+60	+30
Maximum drag force	+75	-45
Maximum lift force	+120	-45
Maximum crush force	+30	+30

Table 3. Combinations among characteristic positions, operational states and load actions to study CSPs in the context of LS analyses

Characteristic positions → **Operational states ↓**			**-120°**	**-30°**	**0°**	**30°**	**60°**	**75°**
v_{ref} [m/sec]		**Limit state**						
7	W_1	SLS		Y				
14	W_2	SLS					Y	
21	W_3	ULS	Y	Y	Y	Y	Y	Y
28	W_4	ULS	Y		Y			

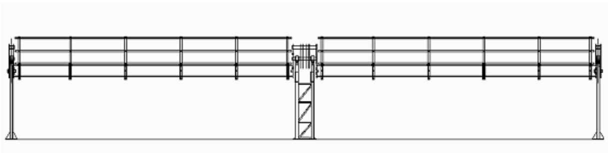
6 ANALYSIS AND VERIFICATION OF THE CONCENTRATION SYSTEM

The concentration system is composed by three main elements: centering, stringers and reflecting mirrors (Figure 4). The details of the adopted materials have already been reported in [4] and they will not be repeated here. The system has been analyzed considering a single modulus of 12 m, reproducing also the torque tube on which the centerings are linked.

6.1 *Limit states and load combinations*

As already reported in the previous Section, the considered limit states and load combinations are summarized in Table 4. Correspondingly, OSs W_1 and W_2 are associated to SLSs for which the wind loads refer to a medium velocity and the serviceability limits referring to maximum torsion and maximum deformation, respectively, must be verified. Differently, in the ULSs W_3 and W_4 the structural permanence within the elastic state as well as tightness under loads corresponding to a characteristic peak wind must be verified. Particularly, in the W_4 state the possible presence of snow has to be additionally accounted for. In both ULSs, a structural instability verification has to be conducted.

A series of possible load combinations have been considered for developing the above-mentioned verifications. It is to be noticed that for the collapse ULS, in addition to the combinations required by the Recommendations, two other combinations have been evaluated in which the snow and the wind alone are present: this was necessarily done due to the fact that the concurrent presence of the two loads, if from one side it increases the acting forces, from the other it reduces the magnitude of the torque bending, so reducing the stress state in some fundamental structural components. All the analyses have been performed in an elastic state and just in those cases, corresponding to a collapse ULS, in which the structure is particularly stressed, a tightness evaluation within a plastic state has been conducted.



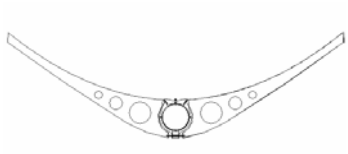


Figure 4: Sketch of the solar collector (portion), left, and sketch of a typical centering, right.

Table 4. Summary of adopted limit states and load combinations for the concentration system.

Operational states	V_{ref} (m/s) @10m	Limit state	Reference velocity
W₁	7	Serviceability	Medium
W₂	14	Serviceability	Medium
W₃	21	Ultimate, Elastic	Peak
W₄	28	Ultimate, Collapse	Peak

6.2 *Analysis methodologies*

The structural elements have been studied through the F.E. Cast3M code [10], setting up a 3D model of the 12 m concentration system (Figure 5). Reflecting mirrors, centerings, stringers, torque tube and edge plates. Apart from the plates, which have been modeled through infinitely-rigid beams, all the other components, being made by thin plates, have been modeled through 2D shell elements, able to take into account membrane as well as bending and shear stresses.

The global structural constraints, applied to the edges of the connecting plates, have been applied such to create an isolated and isostatic system, so the stress state doesn't take into account for possible loads transmitted by the adjacent modules.

It has been evidenced by the analyses that in both elastic and collapse ULSs the safety factors are generally lower than one; by examining the results in more detail, it has been found that local plasticization occur in the higher and middle part of the centering and in some zones connecting the centering with the stringers. Anyway, it is to be said that the model has been developed to study the global stress level in the various components and not to locally analyze the connecting constructive details which need specific 3D models; possible local overcome in the stress yield limit and/or consequent re-distributions of stresses can't be caught by such an approach and they have been investigated elsewhere.

7 TWO-TANKS CSP SYSTEMS

The main advantage of thermal solar power plants is the possibility to use relatively economical storage systems, if compared to other renewable energies (i.e. photo-voltaic and wind). Storing electricity is much more expensive than storing thermal energy itself. Thermal Energy Storage (TES) option can collect energy in order to shift its use to later times, or to smooth out the plant output during irregularly cloudy weather conditions. Hence, the functional operativeness of a solar thermal power plant can be extended beyond periods of no solar radiation without the need of burning fossil fuel. Periods of mismatch among energy supplied by the sun and energy demand can be reduced. Economic thermal storage is a technological key issue for the future success of solar thermal technologies.

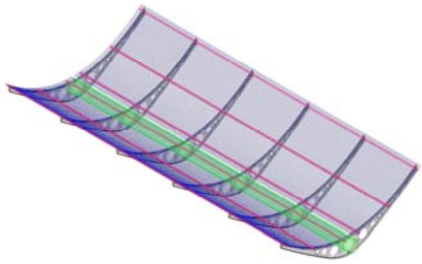


Figure 5: 3D F.E. model of the concentration system.

In our days, among eight thermal storage systems in thermo-electric solar plants, seven have been of experimental or prototypal nature and only one has been a commercial unit. All systems are "at sensible heat storage": two single-tanks oil thermo-cline systems, four two-tanks single medium systems (one oil- and three molten salt-) and two single-tanks double medium systems. Actually the most advanced technology for heat storage in solar towers and through collector plants considers the use of a two-tanks molten salt system [2]. The hot and cold tanks are located on the ground and they are characterized by an internal circumferential and longitudinally-wrinkled liner, appropriately thermally insulated. The cost of the liner is the primary cost of such a tank. In recent studies it has been shown that an increase in the hourly capacity accumulation reduces sensibly the cost of the produced electrical energy (LEC); this leads to increase the reservoir dimensions from the 11.6 m diameter and 8.5 m height of the Solar Two power plant to the larger 18.9 m diameter and 2.5 height calculated in the Solar Tres power plant design phase.

Already in 1985, the Solar Energy Research Institute (SERI) commissioned the conceptual design of a below-grade cone shape storage (Figure 1) with 900°C molten carbonate salts [11]. This solution, even though interesting because of the use of low cost structural materials, showed some limits connected to the high level of corrosion induced by carbonate and high temperature.

In our research, such a type of storage is reconsidered in combination with nitrate molten salts at a maximum temperature of 565°C, using an innovative high performance concrete (HPC) for the tanks (together with stainless steel bars). From the technological point of view, the innovations rely in: higher structural safety related to the reduced settlements; employment of HPC containment structures and foundations characterized by lower costs with respect to stainless steel structures; substitution of highly expensive corrugated steel liners with plane stainless liners taking advantage of the geometric compensation of thermal dilations due to the conical shape of the tank; possibility of employing freezing passive systems for the concrete basement made of HPC, able to sustain temperature levels higher than those for OPC; fewer problems when the tank is located on low-strength soils.

The planned research activities required the upgrade of a F.E. coupled model for heat and mass transport (plus mechanical balance) to estimate concrete tanks durability under prolonged thermal loads and cyclic temperature variations due to changes in the salts level. The presence of a surrounding soil volume has been additionally accounted for to evaluate environmental risk scenarios [3]. The study has allowed for estimating the durability performances of the tank: after about one month, all the structure is fully heated, possibly inducing thermal damage within concrete; such a result is slightly modified when modeling the domain more in detail, i.e. tank plus surrounding ground, or when changes in the salts level are considered. Even if at present some geometric and mechanical characteristics are still to be fixed and consequently they induce an unavoidable uncertainty on the numerical results, the generality of the approach is not affected by such restrictions, and the results can be evaluated just as first guidelines in defining design criteria for liquid salts concrete systems. In fact, this study is the first step in a new research field and will be extended within the Italian Research Project "Elioslab – Research Laboratory for Solar Technologies at High Temperatures" started at the end of 2007.

Additionally, independently of the specificity and interest of the application, it has been shown that the adopted fully coupled mathematical-numerical model (whose details have not been reported here for brevity; the reader is referred to [3, 12-14]), enhanced through additional constitutive relationships for innovative materials, has allowed for obtaining more complete results in terms of water vapour pressure, gas pressure and capillary pressure which become fundamental variables mainly when higher temperature regimes are to be considered.

8 CONCLUSIONS

A new research devoted to the design of parabolic-trough systems for solar power plants has been described in its main lines, as well as the most recent innovations in terms of modeling heat storage concrete tanks for molten salts have been briefly reported.

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