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DESIGNING OF PARABOLIC TROUGH SOLAR CONCENTRATOR USING STRUCTURAL STEEL

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Abstract:
As the exploitation of solar energy has taken place in the field of R&D, structural steel has become a major part of the design and development of the next generation collectors. The design practice used in India and in the Asian community has been considered in major designing and has been considered as a new approach in analysing the wind-load, dead load conditions. These load conditions have been evaluated and analysed at various angular positions of the collector. The optimum dimension for some elements due to the state of the art design has been described in this work and has been highlighted.

Keywords: *concentrated solar power, design criteria, trough concentrator, state of the art design*

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I. INTRODUCTION

The problems concerning the use of CSP technologies has been analysed and reported by several authors, Sargent & Lundy Consulting Group [1] concludes that the CSP technology is an established and reliable solution for energy production, even if its major disadvantage is that the energy produced is at a much higher cost than those required by fossil fuels. The authors pro-pose to enlarge the market of these technologies and increase utilization, thus reducing costs [2]. Price et al. [3] discuss how a torque box design for parabolic trough collectors, reduces weight and the number of deformations of collector structures. Lowering weight and deformations will subsequently reduce the number of drives and interconnecting pipes by allowing more collector elements onto one drive. By using this design of parabolic trough collector, the potential for very large cost reductions comes out. Lüpfert et al. [4] discuss how the existing parabolic trough power plants are a capable and ever-growing technology and, thanks to improvements reached through R&D, it is likely that costs will consistently decrease while advantages and technology rapidly increase. As a major objective towards cost reduction, the authors have aimed to introduce a set of innovations, concerning: issues such as (a) 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 Chemical industries; (b) 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 (c) The thermal storage, it allows the storage of solar energy, which is then used when energy is not directly avail-able from the sun. After some years of R&D activities, ICT has built an experimental setup at the Research Centre in Mumbai, which incorporates the main proposed innovative elements and thermal performance [5] as shown in Fig. 1. The next step is to test these innovations at full scale by means of a demonstration plant.

Fig.1 Parabolic trough solar collector at MVP

The objective of this work is to propose a classification of such structures and, consequently, the design criteria to be followed. However, this should be done with the aim to obtain a compromise between reaching a sufficient safety level and an adequate budget. The problem of designing linear parabolic solar concentrators is given by the necessity of defining both suitable criteria for assigning an appropriate classification for the structure and a new, appropriate design guide referring to existing ISO standards.

II. BRIEF 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 [6]. 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 as shown in Fig. 2.

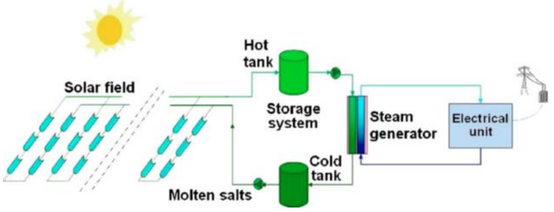

Fig.2 Functional thermodynamic process flow of a solar plant

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 [7]. 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 coaxial 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 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 of three systems: the concentration, the torque, and the support system.

In Table 1, the subsystems and basic elements characterizing the structure of the concentrator are shown. All elements should be considered when designing a parabolic-trough concentrator and verified for “operational” and “survival” load conditions. Corrosion risks and safe life for about 30 to 35 years must be taken into account.

The following basic operational conditions, listed in Table 2, can be can be considered valid for a parabolic-trough concentrator; they define different performance levels under wind conditions. Consequently, “design conditions” can be fixed. Finally, on the basis of what has been previously described, 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 protection. 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 unlimited plant costs lead to non-competitive sources employments. This can lead to tolerate fixed damage levels of the structure under extreme conditions.

Table 1 Structural elements of a PTC

Systems	*Subsystems*	*Elements*
Concentration system	Reflecting surfaces, Mirrors support structures	Reflective mirrors, mirror structure blades, parabolic blades, torque tube, holding plates
Torque system	Torque tube, plate, hinge	Torque tube, torque tube mountings, hinge plates connection, Hinges
Module supports	Intermediate/ final pylons, central support pylon	Cylindrical pin joint, pin joint—support connection, framed structure, plate, hardened steel bolts, mounting bolts.
Other hardware's	Foundations Drive system	Piles and/or plinths, anchor bolts etc.

Table 2 Operating conditions

Stages	Applicable condition
W1	Response under normal operational conditions with light winds
W2	Response under normal operational conditions with medium winds.
W3	Transition between normal operating conditions and survival positions under medium-to-strong or strong winds.
W4	Survival under strong winds in "rest" positions.

III. MATERIALS AND METHODS

The solar concentrator supporting structure is made of structural C-channel steel. Hence, according to ISO standards, steels in the form of bars, plates, or tubes must be of the types shown in Table 3. However, recommendations allow for using different types of steel once the ensured safety level remains the same, justifying this through appropriate theoretical and experimental documentations. Under uniaxial stress states, their design strengths can be deduced from Table 3; in case of multiaxial states, suitable combinations are additionally given. In calculations, the following material characteristics are considered: Young's modulus E=210,000 N/mm2, Poisson coefficient = 0.3, thermal expansion coefficient α =12x10−6° C−1 and density ρ =7850 kg/m^3.

IV. EXPERIMENTATION

Given the design loads, subdivided into 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 (as mentioned in Sec. 4.2). The role of the snow and of other possible variable loads coming from thermal actions or differential settlements at foundations level has also been considered.

A. Fixed loading

Self-weight is practically the only fixed load for the solar concentrator, evaluated from the density of each employed material. In case of nonlinear and/or dynamic analyses, stresses due to self-weight must be superimposed to those generated by such analyses.

B. Variable loading

i. Wind loading on the trough: The mean value of wind velocity, as a function of the distance from soil $V_m(z)$, is expressed by

$$V_m(z) = C_r(z)C_t(z)V_{ref} \qquad \text{(eqn. 1)}$$

where V_{ref} is the reference wind velocity, $C_r(z)$ the roughness coefficient, and $C_t(z)$ the topographic coefficient. The reference wind velocity V_{ref} is defined as the mean wind speed over a time period of 10 min, at 5 m height on a soil, with a 25 year "return period." The site is located in the city and has an operating wind speed of ~3 to 5m/s. It can be evaluated as

$$V_{peak}(z) = G(z)V_m(z) \qquad \text{(eqn. 2)}$$

where G(z) is the 'peak factor' i.e.

$$G = \sqrt{(1 + (\frac{7}{C_t(z)\ln\left(\frac{z}{z_0}\right)})} \qquad \text{(eqn. 2)}$$

Usually G is comprised between 1.4 and 1.5. It should be emphasized that the check under failure loads must be necessarily performed on the basis of the peak velocity, since this gives an overload capable of making the material reach its strength limit, even if its duration is short. As far as the operational performance is concerned, it is more feasible to use the mean velocity. The roughness coefficient $C_r(z)$ takes into account the variability of the mean wind speed and the site characteristics by considering the height over the soil and the soil roughness as functions of the wind direction. The roughness coefficient at height z is defined by the logarithmic profile where k_r is the soil factor and z_0 is the roughness length, both related to the soil exposure category on its turn linked to the geographic location of the investigated area within Mumbai and on the basis of the soil roughness. In case of an open country, k_r is 0.2 and z_0 is 0.08 m. The topographic coefficient $C_t(z)$ takes into account the increment in the mean wind speed on escarpments and isolated hills; in our case, C_t=1 can be taken.

The solar concentrator shape is taken into account by means of aerodynamic coefficients. The different aerodynamic shape coefficients have been determined as per the CFD analysis carried out in similar pattern as shown in [8]. These coefficients have been determined starting from wind actions exerted on the linear parabolic collector as functions of its angular position Fig. 3. Such coefficients have been calculated and shown in Fig. 4 as an external behaviour and the least is shown in Fig. 5 as the 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.

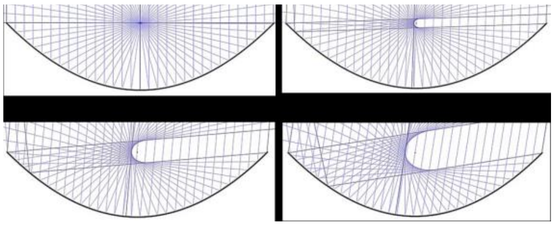

Fig. 3 Parabolic concentrator scheme at different angular positions

Full tables for shape coefficients in case of “external” parabolas as well as “internal” ones are considered similar as reported in [9] and used in [8] 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 deg. 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 4.

It is possible to determine the corresponding effects referring to the following relationships w.r.t the shape coefficients:

Drag force	$F_x = q(V_r)C_e(z)C_{fx}(\alpha)A$
Lift force	$F_y = q(V_r)C_e(z)C_{fy}(\alpha)A$
Torsion	$M_z = q(V_r)C_e(z)C_{mz}(\alpha)Aa$
Mean pressure	$P_m = q(V_r)C_e(z)C_{pm}(\alpha)$
Pressure distribution	$P(x) = q(V_r)C_e(z)C_p(\alpha, x)$

Where

$q(V_r) = \dfrac{V^2}{1.6}$	reference dynamic pressure (N/m^2)
$C_e(z) = C_r^2(z)G^2(z)$	exposure coefficient

and with

z =	Height from ground soil (m)
α =	angular collector position (deg)
x =	Coordinate along the parabola’s aperture
V_r =	Wind velocity at 05 m height (m/s)
k_r, z_0 =	parameters function of the site exposure category
A =	collector area (m^2)
a =	a= collector aperture (m)

ii. Other loading on the trough:

Variable loads must be taken into account in the design of solar concentrators. Some of them are listed below-

• Thermal loads: Temperature variations are considered with respect to the initial reference one, taken as thermal zero. The maximum yearly thermal variation for exposed steel structures is conventionally taken as ±25°C. Taking the initial reference temperature equal to 20°C, the yearly structural thermal excursion changes between −5°C and 45°C.

• Wind effect on the receiver: Wind effects on the receiver tube generate a pressure that creates a drag force on the tube itself. This load induces shear and bending on the receiver support and torsion on the torque tube. The receiver tube is also subjected to a tangential effect that is, in general, negligible. This effect is function of the parabola position.

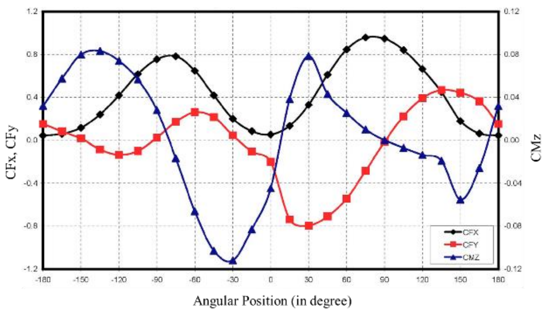

Fig. 4 Angular position of shape coefficients and aerodynamic coefficients of external PTCs

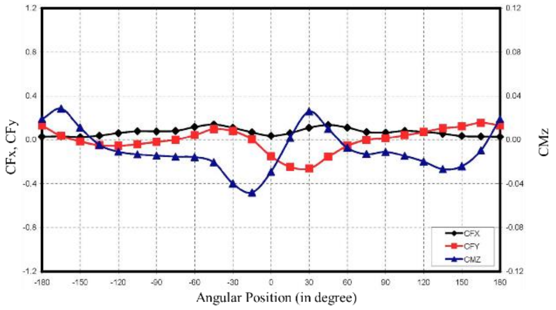

Fig. 5 Angular position of shape coefficients and aerodynamic coefficients of internal PTCs

V. RESULTS AND DISCUSSION

From the analysis it is observed in Fig. 4 and 5, that aerodynamic coefficients and associated loads are largely reduced at the internal collector. The main reason resides in the shielding effect produced by the first collector 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 windbreak barriers and on the realization of “light” collectors only. The position characterized by smaller loads is at 180 deg. 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 deg. The stow position (at 0 deg) does not guarantee an adequate level of protection for the mirrors. All the positions shown in Table 4 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 a consequence of the fact that torque effects are accumulated along the entire 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 concentrator wind design.

Table 4 Effect of wind w.r.t positions on internal and external collectors

Characteristic effect	Angular position (degrees)	
	Internal collectors	External collectors
Safety position	-120	-120
Stow position	0	0
Maximum effect of torque	-15	-30
Maximum torque tube bending action	+30	+60
Maximum lift force	-45	+120
Maximum drag force	-45	+75
Maximum crush force	+30	+30

Following this method, the following steps should be taken:

- Define the design load combinations
- Evaluate the ultimate strength at critical sections of the structure whose material admits an elasto-plastic behaviour, with possible redistribution of stresses
- Calculate the multiplier of each design load combination to obtain collapse of the structure
- Check that the multiplier is higher than one and that the load combination does not reach the ultimate limit state

A simpler strategy based on the elastic analysis has to be performed; “conventional” ULSs can be defined once the yield stress is reached in some sections of the structure. The following proposed procedure shall be follows:

- Define the design load combinations
- Build a reasonable structural model through criteria driven by the limit state analysis, possibly accepting the formation of plastic hinges in areas not affected by instability phenomena
- Search for a distribution of self-equilibrated internal stresses, by means of an elastic analysis
- Check that the distribution of internal stresses is in accordance with the strength criteria and does not cause instability phenomena on the structural elements. This can be safely carried out by checking that the yielding stress is not overcome at any section.

It is assumed that the effects of the previously defined design actions, neglecting instability phenomena, do not cause the unit deformation corresponding to the elastic limit of the material to be overcome; $\gamma_m = 1.0$ is considered. In this case, an elastic analysis is accepted.

VI. CONCLUSIONS

Starting from a preliminary exam of the parabolic-trough collector structure, together with the knowledge of ISO standards, it has been possible to classify the concentrator as a cost effective structure. The above classification has allowed the authors to extract all the desired recommendations useful for designing and checking solar concentrators, performing this according to adequate mechanical design guidelines. Then, complete mechanical guidelines for PTCs have been built and designed at ICT Mumbai, to produce an optimized design capable to ensure high performance and low cost, but also an adequate safety level. These guidelines contain specific references to the load conditions and to the calculation method. As far as loading conditions are concerned, a method to evaluate loads induced by wind and self-loadings has been developed. The analysis has put into evidence that, compared to the 6 m collector line designed using the allowable stresses method, the limit state design leads to a dimensional reduction for some elements, in spite of the load increment due to the doubled length. The details of this application will be described in a future paper together with a discussion on seismic effects, which are being designed now.

VII. ACKNOWLEDGEMENT

The authors wish to acknowledge ICT Mumbai and Marathi Vidnyan Parishad (MVP) for their collaboration in this project work and generously providing financial support for the project activity.

Nomenclature

A = collector area
$C_e(z)$ = exposure factor
C_{fx} = drag coefficient
C_{fy} = lift coefficient
C_{mz} = torque coefficient
C_{pm} = mean pressure coefficient
$C_r(z)$ = roughness factor
$C_t(z)$ = topographic factor
E = Young's modulus
F_r = representative value of an action
F_x = drag force
F_y = lift force
G = shear modulus
G(z) = peak factor
G_k = characteristic value of a permanent action
M_z = torsion
P(x) = pressure distribution
P_m = mean pressure
Q_{k1}= characteristic value of the basic load
Q_{ki} = characteristic value of the accompanying load
R = strength
S = internal stress resultant
$V_m(z)$ = mean wind velocity
$V_{peak}(z)$ = peak wind velocity
V_r = wind velocity at 10 m height
V_{ref} = basic wind velocity
a = collector aperture
f = focus of parabola
f_d = design value of an action
f_k = characteristic value of a material propriety
f_y = yield stress
k_r = terrain factor
p_k = probability value
$q(V_r)$ = basic velocity pressure
q_s = snow load on the roof
q_{sk} = reference value of the snow load on the ground
x = coordinate developed along the parabola aperture
z = height above ground
z_0 = roughness length
Greek Symbols
α = angular position of the collector, angle between the roof and the horizontal
γ_m = material coefficient

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Professor Sudhir V. Panse, is currently associated with Marathi Vidyan Parishad as a managing board member. He was associated with ICT Mumbai as Adjunct Professor in Department of Physics. He is currently acting as a mentor to many research scholars and students in engineering institutes. Research Area-Solar Thermal Technology, Ray Tracing etc.

Professor Jyeshtharaj B. Joshi, is currently working as Professor of Eminence with Institute of Chemical Technology (Mumbai). He is also associated with Marathi Vidnyan Parishad as a President. He is an Indian chemical engineer, nuclear scientist, consultant and teacher, widely known for his innovations in nuclear reactor designs. He is credited with efforts on dissemination of knowledge through over 442 scientific papers published in peer reviewed journals, with over 10772 citations. Research Areas: Fluid Mechanics, Computational Fluid Dynamics, Design of Multiphase Reactors, Absorption of NOx Gases, Renewable Energy Resources.