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A NOVEL BEAM-DOWN SYSTEM FOR SOLAR POWER GENERATION WITH MULTI-RING CENTRAL REFLECTORS AND MOLTEN SALT THERMAL STORAGE

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Abstract

A new concept of beam-down solar power with thermal storage is proposed. The system is featured in an optical system with multi-ring central reflectors and a liquid film molten salt thermal receiver installed near ground level. Its feasibility study has been carried out and power generation cost as well as EPC cost has been estimated. To compensate the drawback to a beam-down solar concentrating system in optical losses, a new receiver concept of liquid film molten salt thermal receiver is designed to aim at higher thermal efficiency than that of tubular receiver. Molten salt liquid film is formed along the inner surface of the receiver wall. The liquid film flows down by gravity. It is shown that the liquid film receiver has a high heat exchange potential up to 2MW/m^2 of solar beam flux on the inner wall surface and proved to be feasible. Assuming 24 hour continuous power generation located at Almeria Spain, conceptual designs for two capacities of 120MWt (commercial plant) and 20MWt (pilot plant) have been made. The height and the radius of the central receiver have been optimized as a result of trade off of optical loss and the cost of the central reflector and its support structure. The total cost of the Beam-Down will become 8.37 US cents/kWh, which will be competitive with coal and natural gas, when crude oil cost increases. TITECH (Tokyo Institute of Technology) plans to launch an international program to develop the innovative/cheaper solar tower beam-down concentrating system.

Keywords: beam down, solar tower concentration, central reflector, molten salt, multi-ring central reflectors

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Introduction

The only current demonstrated technology for megawatt-scale solar electricity (Rankine cycle) is the parabolic trough (SEGS power plants located at the Mojave Desert in California). The solar thermal tower power plants are aimed at achieving better efficiency than the SEGS with a number of two-axis tracked mirrors (heliostats) allowing for higher concentrations of solar heat than parabolic troughs. In the solar thermal tower power plants, the receivers are installed on top of a central tower (Tower Top Receiver). The optics and receiver designs tested to date accept solar radiation at intermediate concentration (300-1000suns), and supply heat at intermediate temperature (up to 600 ^{o}C) to a steam Rankine power cycle. Solar One/Two projects [1] and PHOEBUS project [2] are typical examples. The Solar Concentration Off-Tower (SCOT), also called Reflective Tower or Beam-Down, optical configuration was first proposed by Rable [3]. A hyperboloid reflector is installed at the tower top, redirecting the concentrated solar radiation towards a lower focal region near ground level.

Some systems using molten salt as the heat transfer fluid and for thermal storage have been proposed for solar thermal power generation [4-6] and for synthetic fuel production [7-8]. Utilizing molten salt provides capability of the use of high temperature heat (higher than 400 ^{o}C) and stable operation of down stream processes, even 24-hours continuous operation if necessary. We have been developing molten salt solar receivers, in which the molten salt is heated by concentrated solar radiation, in the Solar Hybrid Fuel Project of Japan [7-8]. In the Project, a beam-down type solar concentration system was selected. In this concentration system, a solar receiver is set up so that its aperture faces upward. This brings an advantage that a large receiver could be installed stably (Beam- Down Receiver). This new type of Beam-Down Receiver brings an advantage that the out side of the receiver can be covered with thermal insulation, therefore radiation heat loss from the receiver is lower compared with the Tower Top Receiver. Beam-down concept has been recognized to be attractive because of its superior feature that heavy receiver may be placed on/near the ground. It, however, has technological difficulties, which has prevented its realization. They are mechanical integrity of central reflector against wind force, wider focus and dilution of beam concentration at receiver aperture, heliostat field configuration, and so on.

To solve this design issue newly developed beam down system was designed, which was equipped with multi-ring central reflectors, molten salt liquid film receiver, heliostat with self-configuration controlling system and new heliostat arrangement of the Dual Tower Concept etc. With these elements, its initial investment is expected to reduce compared to the conventional practice.

Beam-down solar thermal plant system

Figure 1 shows the Beam-Down energy flow diagram. The Beam-Down Receiver design (BD-receiver) consists of a cone shaped receptacle, in which the molten salt films flows internally. Beam-down system (BDS) collects concentrated solar beam near the ground unlike tower-top system. This feature may result in no need of power for pumping up heating medium to the top of the tower. The beam- down system is equipped with a central reflector to redirect a beam reflected from heliostats downward to the receiver on the ground. This may raise design issues such as additional optical losses by the dilution of the beam due to a longer beam path and an increased number of reflections.

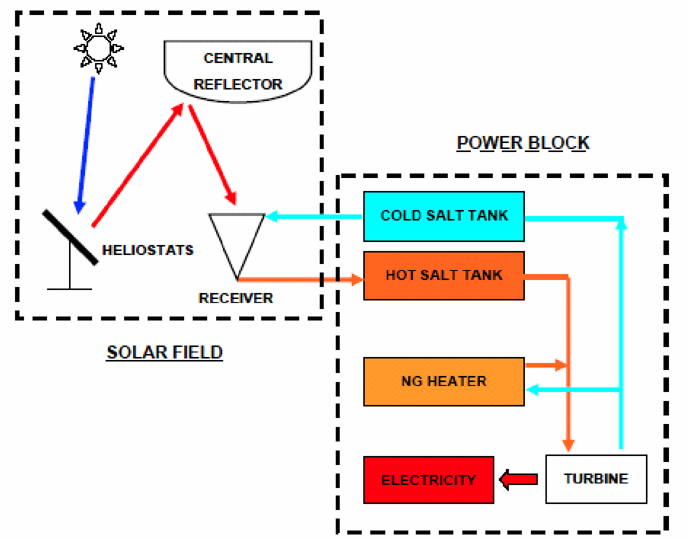

Fig. 1 Beam-Down energy flow diagram.

Whenever receiver is started, molten salt comes from cold tank and feeds the salt distribution system, using the cold salt pump. This cold salt is heated up in the receiver during receiver start up increasing its temperature. Salt will be re-circulated through receiver bypass line until hot salt design temperature is reached. In this moment, plant operator will close bypass line and hot salt will be redirected to the hot tank. The turbine will not be started until hot salt has reached a minimum level in the tank. This is because if turbine is started, it has to be operating for a minimum time period established to avoid frequent start ups, which can affect seriously turbine durability. The hot salt will be cooled down in the stream generator system and redirected to the cold tank. When the hot tank energy is reaching its minimum load to prevent the preheat phase the next time turbine is started. In this mode, a reduced hot salt flow is maintained. This salt flow produces the necessary stream to maintain the turbine at minimum load. Depending on turbine design, electrical energy will be produced or not at this minimum load.

Feasibility study for BDS pilot plant

The feasibility study for the first project phase for a BDS Pilot Plant to be constructed in Almería, Spain entitled “Solar Thermal Electricity Production using Beam Down Solar Concentration System” was performed at the beginning of 2005. Several tasks were carried out in order to 1) study the feasibility of the Pilot Plant for Spain and 2) assess the viability of a Commercial Plant. The following figure presents the strategy followed:

SENSOL (a new software developed by SENER for solar projects analysis) was modified to include an additional module for Beam Down System calculations. Main modifications were focused on calculating heliostat field optical performance with a high accuracy by a ray tracing method. Modelization of the rest of the plant (storage system and power block) was already included in SENSOL module for Central Receiver Systems and was easily adapted to Pilot Plant basic design.

The former item was a key action since field performance (heliostat + reflector + receiver) is strongly dependent on heliostat design, central reflector configuration and receiver performance. A precise tool was then necessary to analyze in deep care all the variables involved in the process and find the optimum lay out (combination of parameters) within the whole design range. Figures 2 and 3 show several SENSOL features for BDS applications.

Field design (Fig. 2): The layout of an optical system comprising a field of heliostats surrounding a central tower concentrator is effective in obtaining the high concentrated solar radiation.

Ray tracing module (Fig. 3): Reflected image at receiver aperture height for a large area heliostat (left) and a small area heliostat (right). Above images demonstrate the reflected images for ideal heliostat and reflector (no errors, hyperbolic surfaces for reflector). On the other hand, below images demonstrate those for real heliostat and reflector (errors, reflector composed of facets).

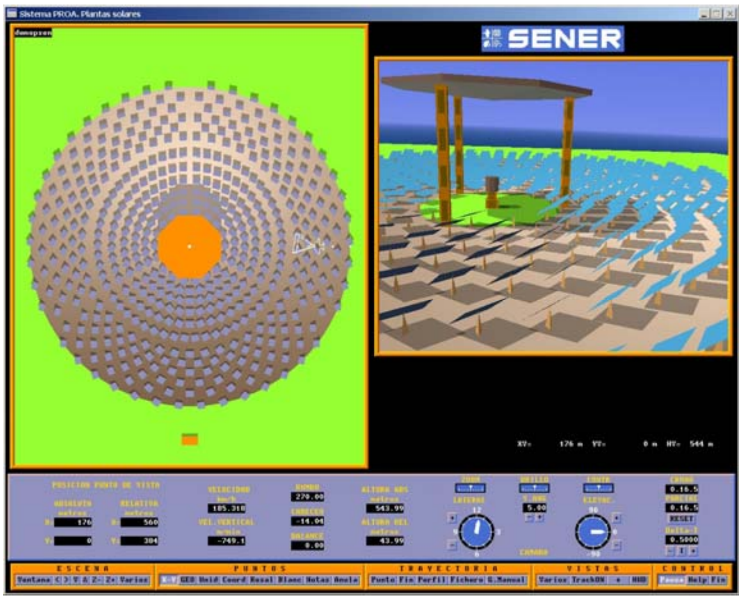

Fig. 2 Field design with SENSOL for BDS applications.

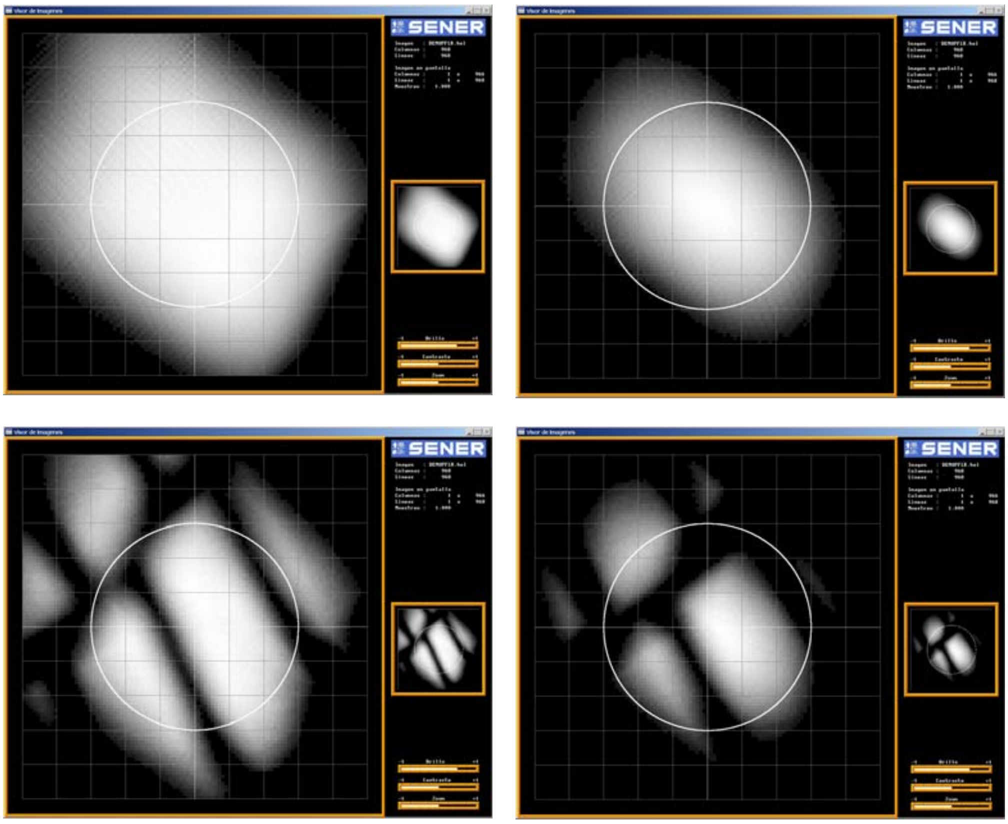

Fig. 3 Ray tracing module with SENSOL for BDS applications.

Conceptual design of the BDS Pilot Plant was based on a cost parameterization. The base case was extracted from the optimum design range composed of all the possibilities analyzed. Several sensitivity analyses were also performed in order to study the influence of the design parameters on plant production and project profitability. It was derived from these analyses that:

(1) Turbine design belonged to the optimum range for Pilot Plant size.

(2) Receiver was a key point in plant design: by one part, receiver performance had a deep impact on plant production, by the other, receiver represented an important contribution to plant cost (12% approximately).

(3) Heliostat design should be studied further due to its high influence on plant performance and project profitability. On one hand, heliostat field represented half the plant cost, on the other, heliostat optical performance highly affected plant production.

Starting from basic design for the BDS Pilot Plant, a basic design was established for a commercial plant. The preliminary results showed that BDS Commercial Plant was not as profitable as Solar Tres basic design, but the figure of merit was enable to be improved by reducing plant costs and optimizing plant design. Several ways were indicated in order to decrease necessary plant investment, highlighting the importance of heliostat cost. In fact, a reduction of receiver and heliostats cost with the advantages of mixing heliostats fields was able to drive to a figure of merit similar or better than in S3 project. Further exploration of the BDS Commercial Plant design was necessary.

Cost evaluation

Assuming 24 hour continuous power generation located at Almeria Spain, conceptual designs for two capacities of 120MWt (commercial plant) and 20MWt (pilot plant) have been made. The height and the radius of the central receiver have been optimized as a result of trade off of optical loss and the cost of the central reflector and its support structure. Result shows that specific power generation cost for the commercial plant is about two hundred times less than that of the past experience of Nio Sun-shine project in Japan.

In more detail, the methodology adopted in the optimization of the present beam down system is as follows. The upper central reflector structure (Multi-Ring Central Reflectors) (Fig. 4) is to design a Space Truss Structure, with a circular plant section and supported in three points located in the contour of this circle, so that they form an equilateral triangle. This kind of structure can adopt the shape required for the reflector mirror-surface with high accuracy. Thanks to the fabrication method of this structure, the precision on the final shape is maximal. As the area to be cover by the Space Truss Structure is quite big, it is necessary to include a kind of beams over the 2 layer of a usual Space Truss Structure. The beams joint the three supports to constitute the equilateral triangle mentioned above. The Ring Type Reflector solves the problems on the mechanical integrity of central reflector against wind force, wider focus and dilution of beam concentration at receiver aperture. When compared with the Hyperbolic shape reflector, the total cost of upper reflector, cubic truss columns, and foundations for the Ring Type Reflector is about half. The parameters for receiver, storage, heliostat and central reflector of the commercial plant of the beam-down system (17MWe) are given in Table 1.

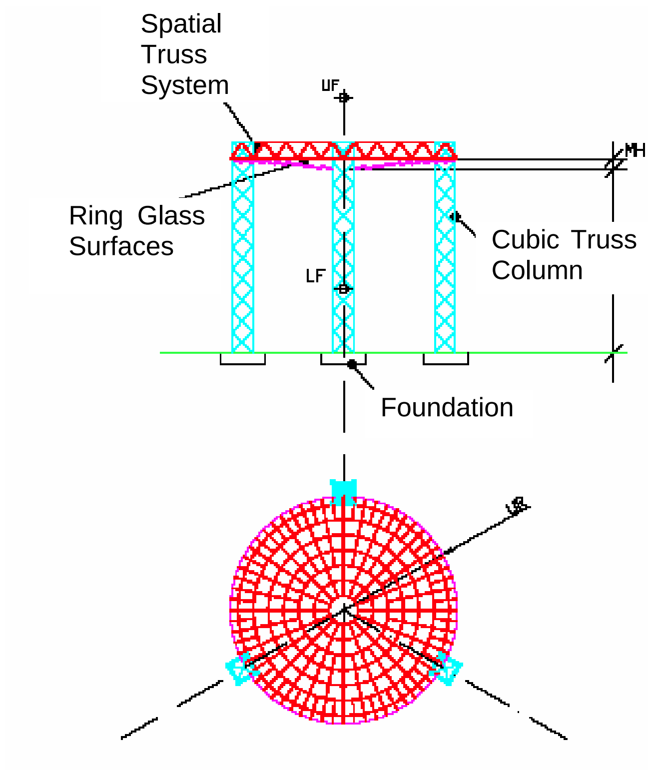

Fig. 4 Multi-ring central reflectors for BDS.

Table 1 Parameters of commercial Beam-Down solar thermal plant system.

SYSTEM	VALUE	DESCRIPTION
HELIOSTAT	10.12m	Heliostat width
	9.78m	Heliostat height
	1.10m	Facet width
	1.06m	Facet height
	9	Number of Facets along heliostat Width
	9	Number of Facets along heliostat Height
	0	Number of Removed Facets
	–	Location of Removed Facets
	27.5mm	Distance between Facets (heliostat Width)
	30mm	Distance between Facets (heliostat Height)
	Flat	Facet shape
	–	Facet Curvature Radius
	89.2%	Mirror reflectivity
	96%	Cleanliness Factor for heliostat facets
	99%	Heliostat Availability
	5	Number of Finite Elements (facet Width)
	5	Number of Finite Elements (facet Height)
	0.725mrad	Elevation Tracking Error (RMS value)
	0.725mrad	Azimuth Tracking Error (RMS value)
	0.768mrad	Horizontal Beam quality Error (RMS value)
	0.768mrad	Vertical Beam quality Error (RMS value)
	0.5%km	Atmospheric attenuation
	0.532°	Solar Disk size
CENTRAL REFLECTOR	Hyperbolic	Reflector shape
	Flat	Mirror shape
	15.5m	Lower Focus Height
	90m	Upper Focus Height
	70m	Focal Radius
	Derived	Inner Edge Angle measured from vertical
	Derived	Outer Edge Angle measured from vertical
	5mm	Allowable Mirror Deviation
	89.2%	Mirror Reflectivity
	96%	Cleanliness Factor for heliostat facets
	10	Number of Rings
	1.175	Ring Progressivity Factor
	0.500	Base Line Factor
	0.5°	Ring Overlap
	2mm	Mirror edge
	0.354mrad	Mirror Horizontal Beam quality Error (RMS value)
	0.354mrad	Mirror Vertical Beam quality Error (RMS value)
RECEIVER	15m	Aperture Diameter
	65.5°	Cone Angle
	15.5m	Aperture Height
	120MWt	Maximum power absorbed by salts
	12MWt	Minimum power absorbed by salts. It is 10% of P_{salt}.
	4%	Receiver solar reflectivity
	14.54kW/m^2	Receiver specific thermal losses for 290℃-565℃
	45min	Minimum time for receiver start op
	6MWht	Minimum heat stored on receiver to start operation
STORAGE	15h	Storage size
	0.5MWt	Tank thermal losses

The cost parameterization of the ring type was carried out in connection with the concept of heliostat field array and the size of the receiver. Then optimal dimensions for the height and the radius of the central reflector were determined. With heliostat array, central reflector dimension and the diameter of the aperture of the receiver given, collector field spillage efficiency (CFSE) and collector field investment (CFI) were obtained. CFSE was defined as the ratio of energy incident on receiver to energy redirected by heliostat field. For example, the reduction of the elevation and the radius of the ring type would give a smaller CFI but a bigger CFSE.

Defining the measure of a kind of specific energy cost as CFI to CFSE ratio R, the optimum dimensions of the reflector were selected so that R could be minimized. Taking commercial plant as an example, the cost impact of the size of a heliostat was identified. Two sizes i.e. 10m*10m and 7m*5m were considered. The latter give noticeably increased plant production with CFSE increased by 11% thanks to additional mirror area and the better spillage efficiency at the receiver aperture than the former while the increase of CFI is limited to 3.6% which could give rise to 7% reduction of R. Through these investigations, the size of optical components and their layout should be optimized in a whole optical system in order to minimize specific energy cost. It is also clarified further technical effort to reduce cost should be in thermal receiver placed on the ground. For this purpose, the concept of cavity type liquid film receiver was seen viable for BDS.

A new receiver concept of liquid film molten salt thermal receiver is designed to aim at higher thermal efficiency than that of tubular receiver. Molten salt liquid film is formed along the inner surface of the receiver wall. The liquid film flows down by gravity. As a component development for the liquid film cavity receiver, simulated experiment using water has been carried out. Correlations for liquid film thickness and temperature distribution in the film have been obtained. It is shown that the liquid film receiver has a high heat exchange potential up to 2MW/m^2 of solar beam flux on the inner wall surface and proved to be feasible. Another concern is mechanical integrity of support structure for the central reflector against wind force. To mitigate wind force, a set of ring type mirrors are incorporated in place of a single reflector.

The BD-receiver collects the energy coming from heliostat field to charge storage system. While reflected rays impact on receiver internal surface, the molten salt film is poured down along receiver wall, thus absorbing the most of the energy impacting on the receiver. This causes an increment in salt temperature from 290^{o}C to 565^{o}C, which are the salt temperatures for the cold and hot tank, respectively. The salt coming from cold tank is heated in the receiver and return to the hot tank. An auxiliary circuit located on receiver upper edge sprays the salt as required depending on irradiation conditions, salt temperature levels and maximum flux during receiver operation. For example, at noon, south part of the receiver will receive more energy from northern heliostats; salt flow will be increased in this zone to reduce temperature gradients over receiver surface. The molten salt storage system consists of two tanks containing the total amount of nitrate molten salts volume. Usually constructed of steel, the tanks can feed the turbine cycle during cloud transients or at night if enough energy has been stored during daytime.

Based on the cost evaluation for the beam-down system with the parameters given in Table 1, the power generation cost was estimated to be 11.71 US cents/kWh, which is graphically illustrated by Fig. 5 along with those for other solar power generation system and fossil fuel-burning power. The data except for Beam-Down are referred to the research paper on the power generation cost in 21 countries by OECD/IEA/NEA. About half of the capital cost of 8.36 US cents /kWh of the Beam-Down is the heliostat cost, then the capital cost will be 7.11 US cents/kWh, when the heliostat cost is reduced by 30%. In this case, the total cost will be 10.46 US cents/kWh. This figure is about two times compared with fossil fuel power cost ; coal (4.38 US cents/kWh) and natural gas (4.81 US cents/kWh), and about half of the solar PV

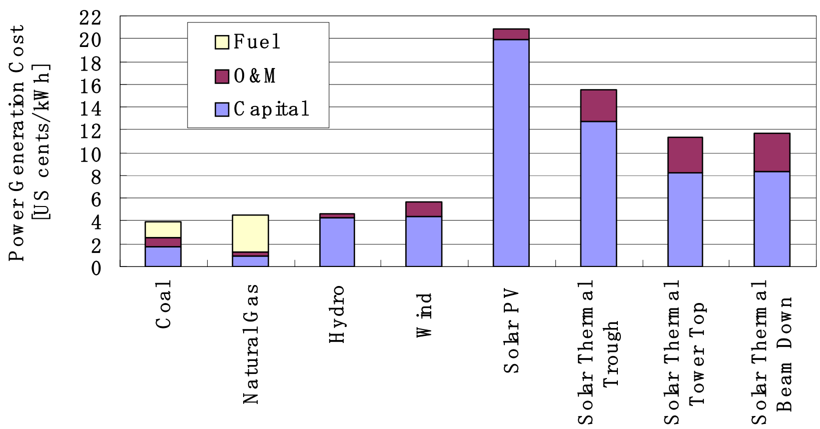

Fig. 5 Power generation cost of renewable energy and fossil energy.

(20.87 US cents/kWh) The cost of 10.46 US cents/kWh can be further reduced by 20%, when the new heliostat arrangement of the Dual Tower Concept is applied (the number of the heliostat and tower height can be reduced). Then the total cost of the Beam-Down will become 8.37 US cents/kWh, which will be competitive with coal and natural gas, when crude oil cost increases. TITECH (Tokyo Institute of Technology) plans to launch an international program to develop the innovative/cheaper solar tower beam-down concentrating system.

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