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Parabolic mirrors for a 100 m-long parabolic trough in Beijing Badaling solar power test plant

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Abstract

From 2009 to 2010, in order to construct a 100m-long parabolic trough in Beijing Badaling solar power test plant, the parabolic mirrors (PMs) were developed by using the car windshield manufacturing technology. The PM in this design consists of a 1.1mm-thick mirror with a back-surface silver coating attached to a glass backing plate preformed to a parabolic shape. The PMs in this design adopted similar automobile windshield manufacturing process. The contours of the PMs were detected using a 3 dimensional coordinate measuring machine (3DCMM). The optical accuracy was obtained by ray tracing, and compared with that of the imported PMs. Through two years of running of the 100m-long parabolic trough, it has been proven that the PMs in this design have good resistance to wind. In addition, the glass backing plate is able to protect 1.1 mm silver mirror from the attack of sand, so the PMs in this design have good anti-sandstorm performance. Therefore, this kind of PMs is suitable for windy and sandy environment condition of areas that fit in with solar thermal power in China, and it should be one of the options for PMs in future parabolic trough solar power plant of China.

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1. Introduction

PMs are an essential part of parabolic trough solar power plant. PMs track the sun so that they can reflect and focus the sunlight onto a receiver containing heat transfer fluid (HTF). The HTF flows through a heat exchanger to generate high-pressure superheated steam. In a Rankine-cycle plant, the superheated steam is fed to a conventional reheat steam turbine/generator to produce electricity.

In most trough power plants built in the world, the adopted PMs are basically single layer monolithic glass mirrors, such as annealed parabolic glass mirrors fabricated by FLABEG, and the tempered parabolic glass mirrors produced by Rioglass Solar using Glasstech curved tempering furnace production line. The architecture of the single layer monolithic glass mirror is illustrated in Figure 1. This type of PMs has been first in service in the SEGS plants which had been built in California, USA during 1980s, and the durability of this kind of PMs is now proven in the field for more than 20 years. In 2012, Chinese Damin Glass and Taiwanglass Group have had the capacity to produce this type mirror using the production lines similar as RIOGLASS, the other similar three lines are under construction in China. Currently, most of the production of this type PMs depends on expensive curved tempering equipment and complex silvering curved mirror processes, so large amount of investment is needed.

Silvered polymers and Aluminized mirrors have been considered as new reflective material. The advantages of these materials are low material cost, light weight, resistance to breakage, flexibility and easiness for transportation. The representative commercial silvered polymers are ReflecTech® Mirror Film[1] and 3M Solar Mirror Film 1100[2], which can be laminated with parabolic shaped smooth substrates to form PMs. ALANOD has developed a front surface aluminized reflector called MIRO- SUN® for outdoor use, the main fields of application for MIRO-SUN® are solar thermal applications or photovoltaic systems [3]. Since the reasons of outdoor durability and the reflectance, these reflector materials described above have not achieved large-scale commercial application.

Mirrors constructed of laminations of thin-glass mirrors to support materials which ensure the accuracy of the parabolic shape have been utilized, examples include Ronda High Tech parabolic cylinder mirrors designed by Ronda High Tech in collaboration with ENEA laboratories, a 1mm mirror is glued to an SMC substrate [4]. Solarlite GmbH has successfully developed a parabolic trough collector (PTC), which is made out of a combination of glass fiber composite material and an efficient thin-film glass mirror [5]. In these structures, the front glasses can be flat, cold bent or heat bent. Once laminated with an appropriate adhesive onto a support material the mirror is perfectly well protected and shows a very high chemical and mechanical durability. The use of thin glass has two main advantages: reducing the effect of solar radiation absorption and reducing the effect of refraction.

In China, the areas suitable for solar thermal power mainly distribute in the north and northwest provinces, such as south of Inner Mongolia, south of Xinjiang, Qinghai, Tibet and Gansu, which is the orange area illustrated in Figure 2 (a). Most of these areas are at high latitude. The natural environment of these areas is different from that of the areas suitable for solar thermal power in other countries. The difference is that these areas have rich wind resources, as shown in Figure 2 (b). These areas are suitable for wind power. In addition, in Inner Mongolia, Gansu, Qinghai and Xinjiang, there are many sandstorm days in a year. For the mirror’s protective layer, sandstorm is a severe test. If single layer monolithic glass mirrors were adopted to parabolic trough power plant in above areas, a
big risk will be taken. This requires that we should develop PMs that are suitable for Chinese situation when we constructed 100 m-long parabolic trough, so we can provide a demonstration for Chinese future parabolic trough solar power plant. The mirrors should have good stiffness and durability, especially the ability to anti-sandstorm.

2. The structure of PMs in this design

Up to now, although a variety of different reflective materials have been developed for sunlight concentration, silvered glass mirrors are currently the only reflective material that has been proven in long-term outdoor applications. Before 2009, there were few reports on developing parabolic glass mirror in China, and no company was able to produce parabolic glass mirrors. It was mainly two reasons, the first was that the process of bending high precision curved glass was not solved and the second was the technology of silvering curved mirror by a wet chemistry process was also not solved. According to the above situation, and the environment of the areas that are suitable for solar thermal power in China, the PMs in this design were determined to be made of laminations of flat thin-glass mirrors to glass backing plate. Its structure is depicted in Figure 3, a 1.1mm-thick silvered glass mirror is laminated to a 4mm glass backing plate with a 0.76mm polyvinyl butyral (PVB) film, 4 ceramic elements are fixed to the back of glass backing plate. The structure of the thin mirror is substantially the same as the structure shown in Figure 1, the difference is that it has only two layers of protective back paint. The width of each PMs in this design is 1.186m, and the length of the curved edge is 1.044m. Each panel's four edges are sealed with silicon, silicon can protect the edges of the thin mirror from corrosion, and can to alleviate impact of other objects on the edges of PM. Additionally, the advantage of using glass as backing plate is that glass backing plate can match the thermal expansion coefficient of the thin glass mirror, besides it can provide a variety of protection to the mirror back coatings, such as resistance to the attacks of sand and blocking the penetration of harmful substances etc. In this structure, the glass backing plate has been parabolic shaped, the flat glass mirror is mechanically deformed into parabolic shape during the lamination process, so that when the PMs are fabricated, the production line of silvering curved glass is without being depended on, only the bending process of high precision parabolic glass is needed to be solved.
3. Manufacturing process

After research and analysis, it was found that the manufacture of PMs could use automobile windshield production technology, so that we could use the existing glass deep-processing equipments to produce PMs for the 100 m-long PTC, in the case of smaller investment of thermal bending mold.

Surface contour accuracy of the parabolic glasses (the glass backing plates) in this design was more accurate than that of typical automotive windshield. Precise control of the entire panel surface contour was required. Therefore, to meet the requirement, forming techniques were modified but were still based on known windshield technology. The hollow-core type thermal bending mold in universal application of automobile industry was modified by the addition of some beams to form a new frame type thermal bending mold shown in Figure 4.

The glass backing plate passed through a bending furnace at a certain speed, was heated to forming temperature, sagged over the female mold, and cooled back to ambient temperature at controlled rate. The glass backing plate could get the parabolic geometry and conserve its smoothness. The glass backing plate inspection measurements were made with a plastic contour gage made by laser cutting. The final contour accuracies were determined by 3 CMM.

The thin mirror and the glass backing plate were laminated with PVB using the automobile windshield laminating process on a laminating mold which was basically the same as the thermal bending mold. The laminating mold was used to assure that the glass backing plate was not deformed during the laminating process, thereby the contour accuracy of the parabolic mirror was ensured. Figure 5(a) shows the finished laminated parabolic mirrors in this design.

Figure 5 (b) shows the 100 meter-long parabolic trough collector array which was built with the laminated PMs in this design in Beijing Badaling solar power test plant in 2010. The paraboloid of this trough was composed of three kinds of the laminated PMs with the same size but different curvatures, as shown in Figure 6.
4. Optical accuracy

The testing was performed using a 3DCMM at the optical laboratory in Badaling solar thermal tower power test plant. As shown in Figure 7(a), the PMs were inspected laying horizontally on its theoretical 4 mounting points. 780 measurement points were uniformly distributed on the PM shown in Figure 7(b). The outer most points were 10 mm away from glass edge. After the detections to each measurement point, the three-dimensional coordinates of each measurement point were obtained. With three-dimensional design software, 1.1mm-thick mirror front surface was able to be fitted based on the three-dimensional coordinates of each measurement point, 1.1mm mirror reflective surface was able to be obtained by offsetting 1.1mm mirror front surface, and 1.1mm thick mirror solid model could also be obtained.

The fitted 1.1mm thick mirror solid model was brought into the optical simulation software for ray tracing. In optical simulation software, material of 1.1mm thick mirror solid model was set to glass, 1.1mm thick mirror convex surface was set to reflecting surface (thus the glass refraction influence on the reflected light was taken into account during ray tracing). 625 incident points were evenly arranged on the mirror reflection surface. Paralleling to the symmetry axis of the parabola, the incident rays which were uniform beams with 0° half angle were projected onto the 1.1mm thick mirror solid model. The amount of the reflected rays projected onto different diameter tubes located on the parabola's focal line was counted. Thus, the percentage that the number of the reflected rays intercepted by the tube accounted for the total number of the incident rays was able to be obtained, this percentage was also called intercept factor.
For the inner mirrors, as shown in Figure 8(a), the intercept factor of the tube of 60mm of diameter located on the parabola's focal line is 100%, the average RMS slope error in transversal direction is 2.2mrad. For the middle mirrors, as shown in Figure 8(b), the intercept factor of the tube of 60mm of diameter located on the parabola's focal line is 98.5%, the intercept factor of the tube of 70mm is 99%, the average RMS slope error in transversal direction is 3.9mrad. For the outer mirror, as shown in Figure 9, the intercept factor of the tube of 60mm of diameter located on the parabola's focal line is 100%, the average RMS slope error of the outer mirrors in transversal direction is 2.7mrad.

In order to compare the PMs in this design with the imported PMs, some imported single layer monolithic PMs were also tested on the same 3DCMM. Figure 10 is the intercept factor curves of the three kinds of PMs in this design and the imported PM for different diameter absorber tube. As seen from Figure 10, for a 60mm tube, the intercept factors for this three kinds of PMs in this design were basically equivalent with that for the imported PMs. But for the tubes of less than 50mm of diameter, the intercept factors for the middle PMs and the outer PMs in this design were lower than that for the imported PMs. These were mainly caused by the local contour errors of the middle PMs’ and the outer PMs’ reflective surface. The causes of the local contour errors were the non-flatness of 1.1mm mirror reflective surface and the non-uniformity of the thickness of the PVB film, but the main reason was that the local contour errors of the glass backing plate. The local contour errors of the glass backing plate were mainly caused by the following points:

- The non-flatness of 4 mm float glass of which the glass backing plate was made.
- The machining errors of the thermal bending mold.
- The deformations of the thermal bending mold during the glass bending process.
• The glass backing plates were not bent to the proper position.
• The gaps between the two beams of the thermal bending mold might cause tiny excessive bending of glass backing plate.
• The deformations of glass backing plate during the annealing process.

Fig. 10. Intercept factor curves

5. Wind resistance performance

A laminated PM in this design was installed on a bracket in our wind tunnel in Beijing Badaling solar power plant for wind resistance test, as shown in Figure 7. When the wind speed reached 30 m/s, the PM was without any damage. 30m/s is the maximum wind speed of our wind tunnel. But according to the literature [6], the breaking wind speed of the laminated PM is above 130 mph, that is about 58 m/s. It is impossible to have such a large wind in inland areas of China.

The climate of the region where Badaling solar power test plant is located has representativeness of the northern climate of China. In Badaling solar power test plant, annual November to next March is the windy season. In windy days, the wind is generally above 4~5 grade. In windy weather conditions, when the imported single layer monolithic PMs are in trembling, the multilayer composite structure PMs in this design are still able to work normally. It is proven that PMs in this design have good stiffness, and are suitable for work in windy environments.

Fig. 11. photograph of wind tunnel test
6. Conclusions

- Utilizing 3DCMM to detect the contours of the PMs in this design, it detected only the front surfaces of the PMs. Although the accuracy of the reflective surfaces of the PMs can be reflected in a certain degree, but because of a parallelism error between the front surface and the reflective surface of 1.1mm-thick mirror, the accuracy of the reflecting surface did not get the most accurately reflected, so a new method to detect reflective surface contour directly is under development in our laboratory.
- Through the testing of the PMs in this design and the ray tracing, it is shown that the PMs produced by windshield forming technology can basically meet the requirements of the parabolic trough collectors with 70mm absorber tube.
- The adaptation of windshield forming technology utilizing a frame type thermal bending mold is a viable process for small batch production. It is also judged that to produce higher precision PMs will require development of new forming mold, and strict control to the thermal bending and annealing process parameters, reducing regional contour error of the glass backing plate.
- Due to the adoption of multilayer composite structure, the PMs in this design have good resistance to wind and sandstorm, it should be one of the options for PMs in future parabolic trough solar power plant of China.

References