Ventana^{TM} Power Train Features and Performance

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Abstract: Most CPV systems are based on Fresnel lenses. Among these, LPI-patented Fresnel-Köhler (FK) concentrator outstands owing to performance and practical reasons. The Ventana^{TM} power train is the first off-the-shelf commercial product based on the FK and comprises both the primary (POE) lenses (a 36-units 1×1 m^2 acrylic panel manufactured by EVONIK and 10×) and glass (or Savosil) secondary optics (SOE). This high concentration optical train (C_g=1,024×, ~250mm optical depth) fits with 5×5 mm^2 (at least) solar cells. The optical train is the fruit of a 1-year development that has included design, modeling, prototyping and characterization, and through the process LPI had the opportunity to find out how well the actual performance correlates with models, but also learned practical aspects of a CPV system of this kind, some of which have very positive impact on system performance and reliability.

Keywords: CPV, solar concentrators, Fresnel lens, Kohler integration

INTRODUCTION

The Concentrated Photovoltaics (CPV) is based on the use of high-efficiency triple-junction solar cells (with efficiencies over 40% in commercial cells already) and on high-performance optics. The goal of this combination is low-cost mass production and long term efficient energy production. Both are possible if the system is simple and mature from the technological standpoint but also when it allows relaxed manufacturing tolerances and high concentrations at the same time. Manufacturing tolerances can be expressed in terms of concentrator acceptance angle (α), usually defined as the incident angle at which the concentrator collects 90% of the on-axis power. This means that the optics shouldn't be too sensitive to different imperfections of the system, namely: (1) shape errors and roughness of the optical surfaces, (2) concentrator module assembly, (3) array installation, (4) tracker-structure finite stiffness, (5) sun-tracking accuracy, (6) solar angular diameter, (7) lens warp, and (8) soiling. Each one of the imperfections can be expressed as a fraction of the tolerance angle, so that, all together, they comprise a "tolerance budget".

Ventana^{TM} is an off-the-shelf commercial product by Evonik and LPI based on FK concentrator [1][2] and is available with PMMA POE lenses and glass (or Savosil) secondary optics. The *FK* mixes simplicity (it is essentially a Fresnel lens, whose technology is quite mature) and excellent performance: high concentration and large tolerances, enabling high array efficiencies, combined with a solar cell illumination free of chromatic aberration [3].

Also in the case of long term reliability the *FK* has advantages: the very uniform irradiance on the receiver cell prevents both cell failure and efficiency drops. Moreover, the input beam is split into four that are focused near the *SOE* top surface: if tracking fails, these spots hit the housing back plate divided and un-concentrated, so damage of concentrator cell assembly (CCA), wires, etc is more unlikely. Besides, the cell is completely embedded into SOE and isolated from humidity, as we discuss below.

LPI has also developed a *SOE* gluing strategy (patent pending) that automatically withdraws air bubbles from top of the solar cell, if they show up in the encapsulation process. This approach facilitates assembling work and reduces mismatch losses since the probability of having some cells producing smaller photocurrents in a series connected row is reduced.

VENTANA^{TM} FEATURES

The Ventana^{TM} primary lenses come in the form of a 1×1m^2 PMMA panel (Figure 1 and Figure 2) comprising 36 units meant to be aligned with 36 SOEs and the correspondent cells.

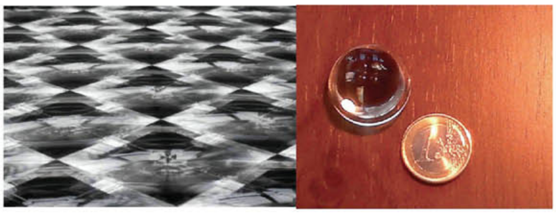

FIGURE 1 Pictures of primary optics panel (left) developed by EVONIK and 10× (see http://lpi-llc.com/Ventana.php) and glass secondary optics (right). Notice both the primary and secondary optics units are divided into four optical sections to perform the Köhler function which enables outstanding irradiance and colour uniformity over the solar cell, while keeping high concentration and acceptance values

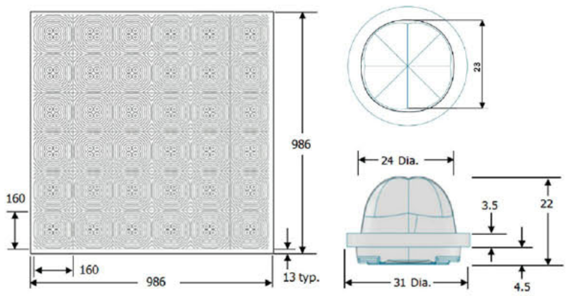

FIGURE 2 VENTANA™: Dimensions of primary and secondary optics, in mm.

Ventana™ has a geometrical concentration of 1024×. Ray trace modeling shows the system attains an optical efficiency above 83%, with an acceptance angle of about 1.1° (FIGURE 3 shows the simulated transmission curve, notice the high acceptance angle when defined at 95% transmission as well). Module efficiency is >32% (when the module utilizes a 39% C3MJ Spectrolab solar cell and without AR coating on SOE), confirming the good performance achieved with previous versions of FK systems [4].

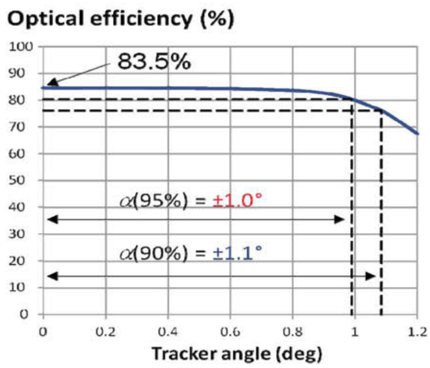

FIGURE 3 Simulated transmission curve. Acceptance angle at 90% of efficiency is ±1.1°, while at 95% of efficiency is still quite high, ranging ±1°.

TABLE 1 shows a summary of the main Ventana™ characteristics.

TABLE 1. Ventana™ characteristics.

Optical Train Efficiency (POE+SOE)	>83%
f-number (height/diagonal aperture)	~1
POE lens size (mm^2)	160x160
Cell illuminated area (mm^2)	5x5
Acceptance angle	±1.1°
Geometrical Concentration	1024×
Module Efficiency (with 39% efficient solar cell; without AR coatings)	>32%

VENTANA™ PERFORMANCE

Measured peak efficiency is over 32% (with only a slight ±0.5% absolute variation in a wide ±10mm range in Z axis shifts of SOE away and towards the POE) using a conventional 39% C3MJ cell, a value that increases an absolute 1.5% (therefore reaching 34%) with the new AR-coated glass SOEs, whose performance has been confirmed both in preliminary laboratory tests (characterization of separate SOE parts transmission) and on the outdoors functional measurements. Similar photocurrent boosts can be expected from Savosil SOEs, currently under development, thanks to their lower absorption. FIGURE 4 shows measured IV-curve, for a system comprising a SOE lacking of AR coating.

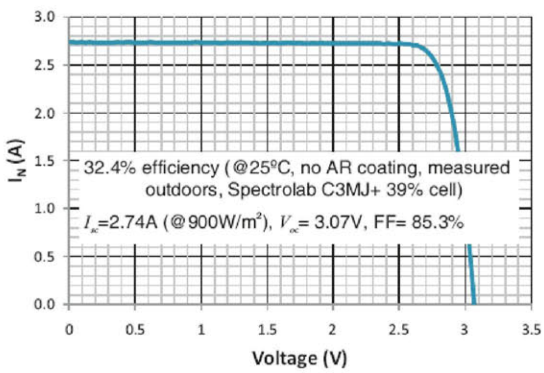

FIGURE 4 VENTANA™ shows 32.4% electrical efficiency (I_{sc}=2.74A @900W/m^2), V_{oc}=3.07V and FF=85.3%) measured outdoors with Spectrolab C3MJ (39% efficiency) calculated at 25°C. No AR coatings.

The measured acceptance angles are ±1.1° (FIGURE 5) perfectly matching the models, while the irradiance pattern on the cell is almost perfectly uniform.

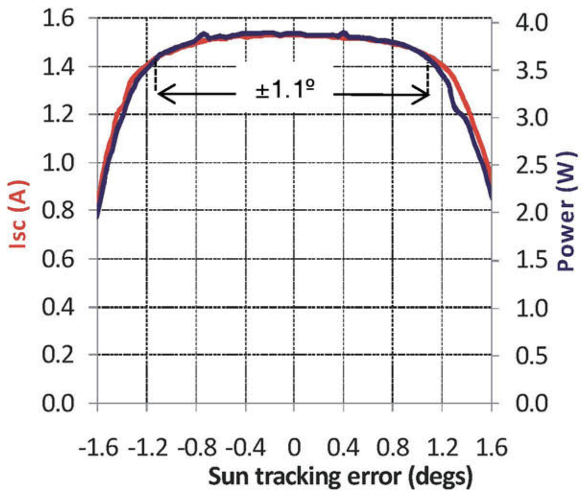

FIGURE 5 Measured Ventana^{TM} performance as a function of sun's incidence angle. The optical efficiency is linked to the photocurrent curve, and the acceptance angle is measured in such curve. Most concentrators show a mismatch between the power or I_{sc} as a function of incidence angle, and such mismatch is caused by chromatic effects most probably.

Notice both the I_{sc} (which is directly linked to the optical efficiency) and the Power have been measured as a function of the incidence angle, showing the evolution is almost identical. This does not hold for all concentrators, where a more rapid drop of the power can be noticed very often. The effect is linked to the chromatic aberration mentioned before: when the light feeding the different sub-cells presents different irradiance profiles (i.e., chromatic dispersion) the Fill Factor FF (and even I_{sc}) will decrease. This drop in FF value depends on the magnitude of dispersion: very dispersive concentrators entail large FF drops, while lower FF drops will be noticed with low-dispersive concentrators, as is the case of the FK [5].

Figure 6 shows the simulated irradiances on the each multi-junction subcell, for normal incidence and at 0.6° off-axis, in the case of the FK concentrator. Both cases show almost perfectly-uniform irradiance distribution at normal incidence and only negligible variation when system is off-axis.

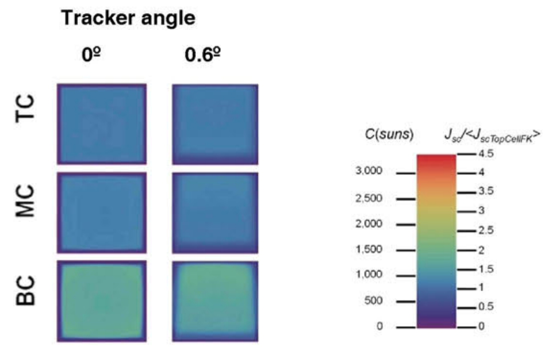

FIGURE 6 Irradiance maps/Normalized photocurrent densities at normal incidence (left) and at 0.6° off-axis incidence (right), for the top cell (TC), middle cell (MC) and bottom cell (BC). 1 sun = 900W/m^2.

Such stability has important performance consequences and explains the perfect matching of Isc and Power curves of **FIGURE 5**. The compared simulated performance of an FK VS another Fresnel-based concentrator (the SILO, which is also based on the Köhler approach [6]) is shown in Figure 7. When the system goes off-axis uniformity for majority of concentrators gets worse, so even if the optical efficiency doesn't drop the produced electrical power decreases significantly, and this holds even for the F-SILO device, whose ability to provide uniform irradiance was considered good if chromatic effects were not taken into account. This is not the case for FK system, whose uniformity is maintained all throughout acceptance angle and sun spectrum.

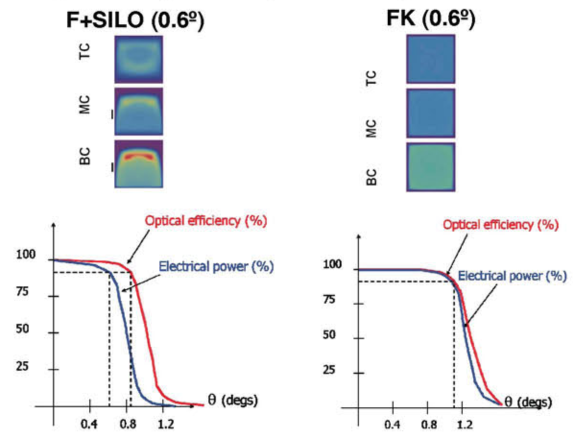

FIGURE 7 The influence of chromatic dispersion of irradiance on the different subcells is evident in the Fresnel-SILO (left) since the electrical power is much more sensitive to the incidence angle than the optical efficiency itself. In the FK concentrator (right) the effect is hardly noticed owing to the well balanced irradiance uniformity, no matter the wavelength of power.

All these excellent on-sun results confirm the FK concentrator as a very attractive and potentially cost-effective solution for the CPV market: notice these have been achieved at the first try, when different mistakes can be committed and parts manufacturing and assembly is not yet tuned. The fact is the FK has enough tolerance-budget to absorb these errors, which remain invisible to the manufacturer.

VENTANA™ RELIABILITY

One practical advantage of FK deals with the way the cell and SOE can be bonded together (Figure 8). On the one hand, glue leakage does not provoke light losses, like in the case of inverted prisms solutions. On the other hand, the gluing procedure can be designed in such a way that the cell ends up isolated from environment.

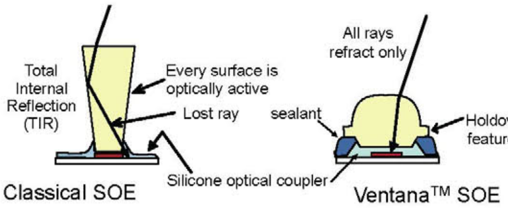

FIGURE 8 Ventana™ SOE can be bonded to the solar cell easily and light spillage does not produce efficiency drops. The bonding can also provide additional cell protection if designed carefully.

The FK SOE is molded in glass with special features at the bottom to enable not only proper alignment with respect to the CCA, but to be let air bubbles (if they show up in the encapsulation process) flow out away from the cell active area before the glue cures, by a simple/automatic gravity-based method (patent pending).

Additionally, the risk of UV solarization in Ventana™ is greatly reduced by splitting the incident beam into 4 channels. Altogether with Evonik 25-years-POE warranty makes Ventana™ highly reliable.

CONCLUSIONS

Module manufacturers using Ventana™ can eliminate the design and tooling costs as well as long lead times required to obtain optics.

Experimental results confirm high performance. Ventana™ combines three main qualities that CPV system should meet:

- Low cost (high concentration, low-cost optics, easy assembly, loose tolerances);
- High performance (high acceptance angle:1.1°; high optical efficiency: >83% and excellent irradiance uniformity);
- High reliability (durable materials, uniform irradiance and system is compatible with excellent cell protection).

ACKNOWLEDGMENTS

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