TOWARDS NOVEL GLAZING WITH SEASONAL DYNAMICS BASED ON MICRO COMPOUND PARABOLIC CONCENTRATORS

Jing Gong[1], André Kostro[2], Andreas Schüler[1]

1 Solar Energy and Building Physics Laboratory, Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

2 BASF Schweiz AG, Klybeckstrasse 141, CH-4057 Basel, Switzerland

Abstract

Thermal loss and overheating caused by glazing is a key issue in reducing CO2 emission and energy consumption of buildings. A novel glazing based on micro compound parabolic concentrators (CPCs) is proposed. The glazing consists of a polymer layer with embedded micro CPCs, which is attached to a glass pane of glazing. Thanks to the geometry and the micrometric size of the embedded CPCs, the proposed novel glazing can reduce energy consumption in cooling, improve visual comfort and maintain clear view through glazing. In the present work, the potential benefits of such glazing are preliminary estimated for Dubai. The seasonal dynamics are investigated by analyzing the direct solar transmittance for the working hours on the spring equinox and the winter solstice. The improvement of visual comfort is studied based on the assessment of glare. First samples with micro CPCs are fabricated, and the high transparency is achieved. The optical characterization using goniophotometer confirms the seasonal dynamics of the novel glazing.

Keywords: Advanced glazing, Microstructures, Compound parabolic concentrators, Seasonal dynamics, Visual comfort.

1. Introduction

The design of highly glazed building has become a worldwide trend in modern architecture. However, glazing may induce large thermal loss in winter while increase cooling load in summer, and it may also cause glare [1, 2, 3]. In the past decades, various glazing systems and daylighting systems have been developed to provide thermal and visual comfort. The “smart windows” coated with electrochromic or thermochromics materials are able to regulate the thermal radiation leading to lower solar gains in summer and higher solar gains in winter [4]. However, different color rendering from the normal spectrum of those windows can reduce the interest to users. A venetian blind should be combined with the electrochromic windows to block direct sunlight in order to avoid glare [5]. Anidolic systems consist of light-redirecting device can be alternatives. However, the installation of an anidolic system which varies in size going from 0.5 to 1 m long can be an architectural challenge [6]. The usage of blinds by occupants is not always made according to the solar availability, and therefore large performance gaps may appear between theoretical prediction and reality. With the use of blinds, the view through glazing will be obstructed.

In order to solve the problems, a multifunctional glazing based on micro compound parabolic concentrators (CPCs) is proposed. An important property of CPCs [7] is acceptance angle. Light arriving within the acceptance angle is concentrated and leaves the concentrator through the exit aperture of the structure, while the light out of acceptance angle will be reflected back to exterior through the input aperture. The glazing consists of a polymer layer with embedded micro CPCs, which is attached to a glass pane of glazing. Thanks to the geometry and the micrometric size of the CPCs, the proposed novel glazing can have the potential advantages with respect to three aspects: reducing energy consumption in cooling, improving visual comfort and clear view through glazing.

In the present work, we focus on the preliminary investigation of the potential advantages of the proposed glazing. The glazing is modelled for ray-tracing simulation, and the angular-dependent transmittance at the azimuth angle of 0˚ is calculated. The potential benefits of such glazing for Dubai are estimated by simlations. Seasonal thermal dynamics is investigated by calculating the direct solar transmittance for the working hours on the winter solstice

doi:10.18086/swc.2017.35.02 Available at http://proceedings.ises.org

and on the spring equinox. The improvement of visual comfort is studied based on the assessment of glare. First samples with micro CPCs are fabricated. Structural characterization by optical microscope is carried out. The redirection performance and the light-blocking ability are qualitatively demonstrated. The optical characterization by goniophotometer is conducted.

2. Methods

The CPC [8] was initially the essential component of a solar concentrator, and generally consist of two symmetric parabolas (named parabola L and parabola R respectively in our case), as shown in Figure 1 (a). The focal point for parabola L (F_L) lies on parabola R, likewise the focal point of parabola R (F_R) lies on parabola L. By definition, the axis of parabola L passes through the focal point of parabola L and the axis of parabola R likewise passes through the focal point of parabola R. The angle that the axes of the parabola L and R make with axis of the CPC defines the acceptance angle of the CPC [9]. All radiations arriving within the acceptance angle is concentrated and leaves the concentrator via the lower exit of the structure, while the radiations out of acceptance angle will be reflected back out through the input aperture.

The program CFSPro [10] which is developed especially for the study of complex fenestration system, is used to obtain the angular-dependent transmittance by ray-tracing simulation. The design of the geometry of the CPC is based on the calculation developed by Rabl [11]. In order to understand the potential benefit of the angular-selective transmittance for the reduction of energy consumption in heating and cooling, simulation referring to the double glazings with CPC30-30 and with CPC40-40 on south-facing facades is conducted for Dubai. In the case study, the transmittance of direct solar light in the visible range is calculated for the working hours (from 8:00 to 17:00) on the winter solstice and on the spring equinox. Monthly average high temperature and average low temperatures are show in Figure 1[12].

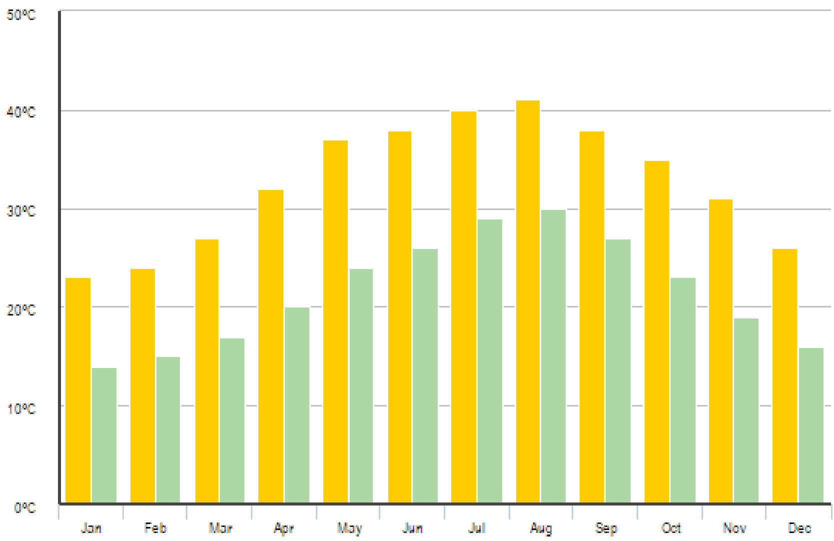

Figure 1 monthly average high and average low temperatures in Dubai.

Comfortable daylight environment in schools and offices can improve the occupants' productivity and tend to reduce the absenteeism [13, 14]. The improvement of daylight environment is investigated with the assessement of the risk of glare by Daylight Glare Index (DGI). A DGI is calculated by

$$DGI = 10log0.478\sum_{i=1}^{n}\frac{L_{s,i}^{1.6}\cdot\Omega_{s,i}^{0.8}}{L_b + 0.07\omega_{s,i}^{0.5}L_{s.i}}$$

where $L_{s,i}$ (cd/m^2) is the luminance of a glare source (i) in the field of view, $\Omega_{s,i}$ (sr) is the solid angle subtended by the source, modified for the effect of the position of the observer in relation to the source, L_b (cd/m^2) is the average luminance of the visual field excluding the glare sources, and $\omega_{s,i}$ (sr) is the solid angle subtended by the glare source.In the present paper, a viewpoints were chosen in the standard Reinhart-defined room [15] with the dimension of 8.2-m long × 3.6-m wide × 2.8-m high. The view point was set at 1-m distance from the window, with a height of 1.25 m and the line of sight points towards the wall, in order to simulate a working position in a realistic state, referred to as employee position. This viewpoint is in the area where direct sunlight was generally received during most of the year with a conventional glazing, and is considered as an uncomfortable position.

The preparation of embedded micro CPCs requires the fabrication and the replication of microstructures, as well as the coating with reflective materials on the selective surfaces of microstructures [16, 17]. The master mold with the desired microstructures for the sample in the present manuscript is produced by laser ablation. In the present work, a PDMS stamp of the negative microstructure with respect to the master mold is prepared. Then another PDMS stamp with the positive microstructure is replicated from the first PDMS stamp. After that, the negative microstructures are replicated from the PDMS positive template by UV-cured acrylated hyperbranched polymer (HBP) on a glass substrate. The selected surfaces of the HBP microstructures on the glass substrate are coated with aluminum by physical vapor deposition. Then the grooves of microstructures are filled with the identical HBP to encapsulate the micro-CPCs, and a sample with clear view is achieved.

3. Results and Discussions

Double glazing with the embedded micro CPCs in a polymer layer, which is attached to the inner side of the outer glass pane, is modeled, as shown in Fig. 1 (a). The refractive indexes of glass and the used polymer are the same (refractive index n = 1.5). The thickness of the glass panes and the thickness of the polymer layer for modelling are bigger by factors of 10-100 than that of reality, for the convenience of viewing. In winter where solar elevation angles are low, the solar radiation is partially redirected by the reflective parabolic surface and then enters in the interior space. In contrast, in summer where the elevation angle is high, the direct solar radiation is reflected outside after two or more reflections. The transmittance of the visible light as the function of elevation angles at the azimuth angle of 0˚ is calculated, for the conventional double glazing and the double glazing integrated with two different geometries of CPCs (Fig. 1 (b)). Symmetric CPC of a half acceptance angle of 30˚ is labelled as CPC30-30 and with a half acceptance angle of 40˚ it is labelled as CPC40-40. Due to the refractive index of 1.5 of the polymer, the incident angles corresponding to the acceptance angles for the two CPCs embedded in the polymer layer are 48.6˚ (CPC30-30) and 74.6˚ (CPC40-40). For CPC30-30, the transmittance is at about 0.64 which is approximately the same as that of the low-e double glazing in the angular range between 0˚ and 25˚. Beyond 25˚, a fraction incident light is redirected by two or more times and then leave the system through the input aperture. Therefore the transmittance significantly reduces beyond 25˚ and reach 0 at about 50˚. Likewise, for CPC40-40, the transmittance stay at 0.72 in the angular range between 0˚ and 12˚. After 12˚ the transmittance gradually reduce, and this trend is unlike that of CPC30˚, as the curvature of the parabolic mirrors is smoother than that of CPC30-30. The transmittance stays at 0 beyond 80˚.

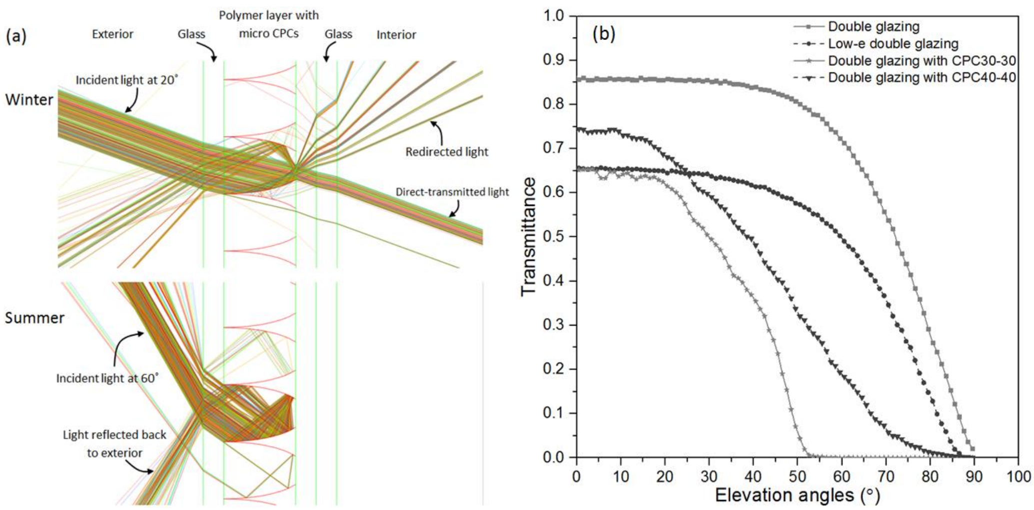

Figure 2: (a) Model of embedded micro CPCs in a polymer layer attached to the inner surface of the outer glass pane of a double glazing for ray-tracing simulation; (b) simulated transmittance as the function of elevation angles of the sun at the azimuth angle of 0˚

In order to understand the potential benefit of the angular-selected transmittance for the reduction of energy consumption in cooling, calculation of direct solar transmittance of visible light is conducted for the working hours (8:00-17:00) on the spring equinox and (b) on the winter solstice for the CPCs applied to a vertical double glazing in Dubai.

For CPC30-30 on the spring equinox, the direct solar transmittance remains at 0 between 10:00 to 15:00, suggesting the potential strong reduction in cooling. The transmittance between 8:00 to 10:00 and 15:00 to 17 is also reduced to the average transmittance of 0.09. On winter solstice, the transmittance from 8:00 to 9:00 and from 16:00-17:00 is similar to that of low-e double glazing. A reduction with the average amplitude of 0.2 is observed between 9:00 and 16:00, and at noon the direct transmittance is reduced from 0.61 to 0.35. Compared with the case on spring equinox, the reduction of the transmittance on winter solstice is moderate. However, a moderate reduction may be preferred, as the average high temperature in Dubai is above 20℃ but not as harsh as that in spring and summer.

For CPC40-40 on the spring equinox, the transmittance from 8:00 to 17:00 remains rather constant at about 0.15. On the winter solstice, the transmittance is modestly reduced. The transmittance is reduced from 0.61 to 0.47 at noon on the winter solstice. Interestingly, the transmittance from 8:00 to 9:00 and from 16:00 to 17:00 is about 0.1 higher than that of low-e double glazing. The increase might contribute to the improvement of thermal comfort in the early morning and in the late afternoon, considering that the average low temperature in December in Dubai is in the order of 15°C.

The conventional double glazing with micro CPCs might not be the best configuration for the application in Dubai. Nonetheless, it shows the working principle of glazing with micro CPCs to achieve the seasonal dynamics. Moreover, the polymer film with embedded micro-CPCs can be attached to large variety of glass panes. In the future, optimization of the configurations will be conducted.

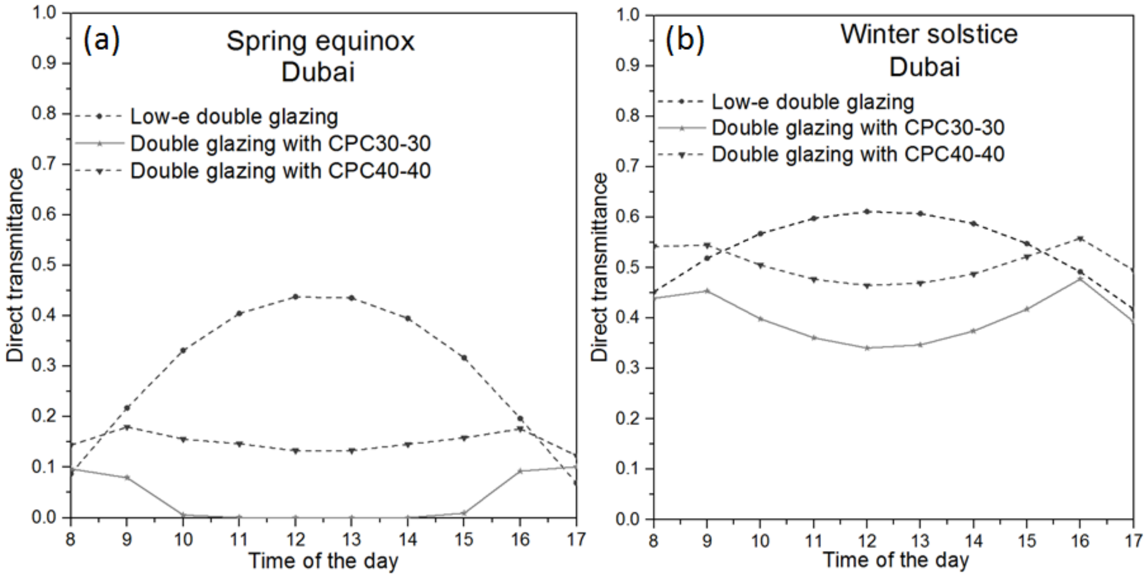

Figure 3: Plots of direct visible solar transmittance of visible light during working hours (8:00-17:00) (a) on the winter Solstice and (b) on the spring equinox for the CPCs applied to a vertical double glazing in Dubai.

Figure 4: The plots of hourly Daylight Glare Index (DGI) values: a) on the spring equinox, and b) on the winter solstice at the employee’s position. Intuitively speaking, glare is likely to happen when the direct light source in the field of view. For the case with low-edouble glazing, the direct sunlight of incident angle larger than 53.5° will not reach the eye of the employee. Therefore, on the spring equinox, the DGI falls in the acceptable level for the three types of glazings during the working hours (from 8:00 to 17:00). On the winter solstice, the improvement of thermal comfort is evident using micro CPCs. The case with low-e double glazing suffers from glare for 60% of the daytime on the spring equinox. The glazing with CPC30-30 and CPC40-40 suppress the risk of glare to only 20% and 30% of the daytime.

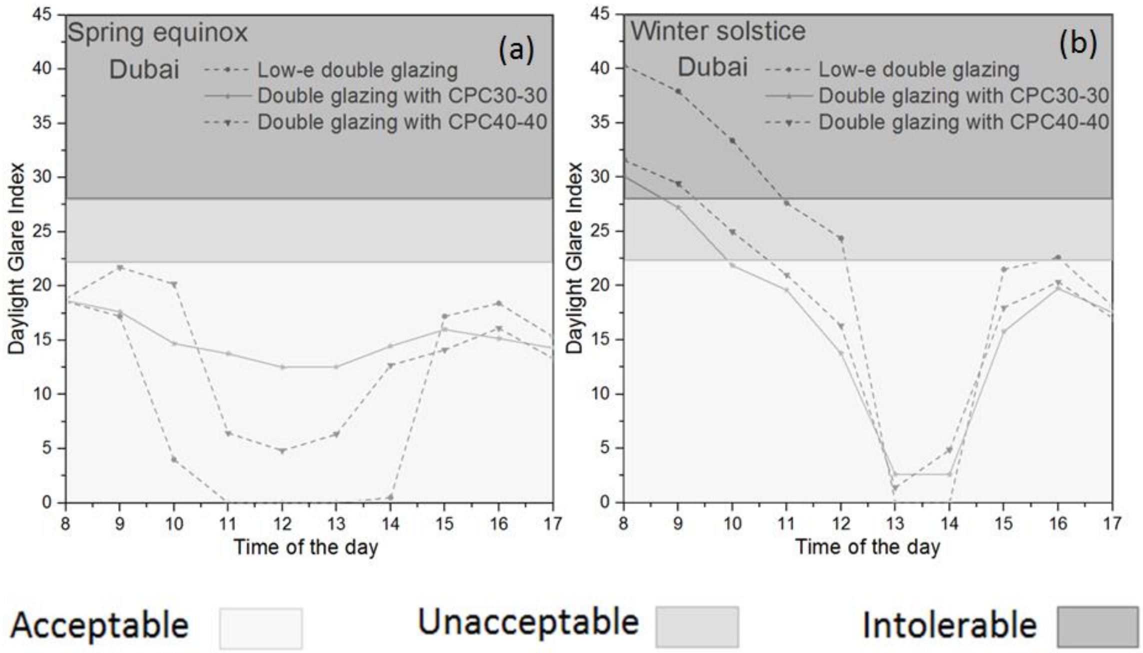

Figure 4: The plots of hourly Daylight Glare Index (DGI) values: a) on the spring equinox, and b) on the winter solstice at the employee's position.

The preparation of embedded micro CPCs requires the fabrication and the replication of microstructures, as well as the deposition with reflective materials on the microstructures [18,19]. An example of the HBP microstructures based on the theoretical design of micro CPC30-30 is shown in Figure 5 (a). The width of the outgoing aperture is 34 µm, and the height of the microstructure is around 80 µm. The dash arrow shows the surface where the highly reflective materials are deposited. In the present work, the thickness of the deposited materials is in the order of 50 nm. Due to the micrometric size of the microstructures, a clear view seen through the glazing with embedded micro-mirrors is achieved, as indicated in Fig. 2 (b). The present sample consists of a single glass pane with an attached polymer layer in which micro CPC30-30 are embedded. The area with micro CPC30-30 is 5 cm x 4 cm. The redirection performance and the blocking ability of the sample are studied with a collimated beam, as indicated in Figure 6 (a). At a low incident angle, the incident light splits into redirected part and direct-transmitted part after going through the CPCs. At a high incident angle, the majority of light is reflected outside after two or more reflections, that explains why the sample looks bright when it is observed from the side of the light source, as shown in Figure 6 (b).

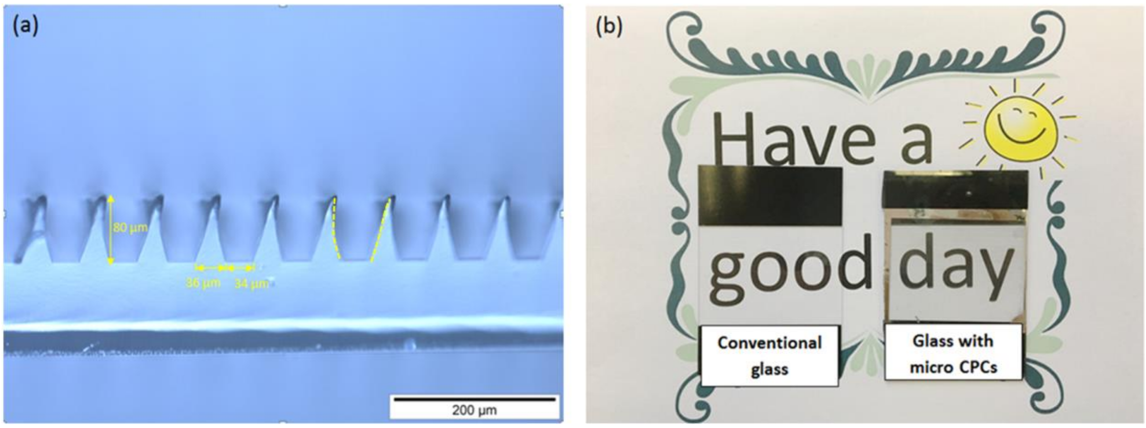

Figure 5: (a) An example of HBP microstructure; (b) the views seen through the conventional glass and the glass with the polymer layer which consists of embedded micro CPCs. The viewing direction is perpendicular to the surface.

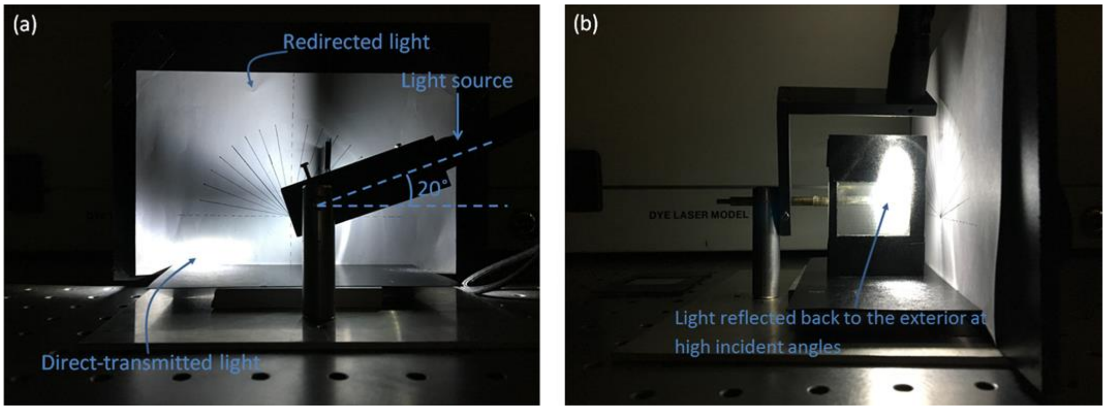

Figure 6: The redirection performance and the blocking ability of the sample are studied with a collimated beam at the incident angle of (a) 20˚ from the front side and (b) 60˚ viewing from the side of the light source.

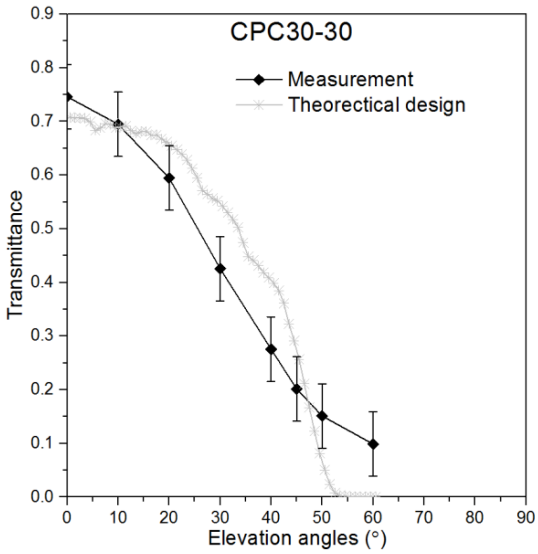

Figure 7: Comparison between the measurement result from goniophotometer and the simulated transmittance.

The angular dependent transmittance is further observed Measurement of transmittance as the function of elevation angles at the azimuth angle of 0˚ is carried out using goniophotometer. As shown in Figure 7, the transmittance reduces with the increase of elevation angle. The transmittance at the elevation angle of 0˚ is about 0.75 while at the elevation angle of 60˚ it is only about 0.1. The optical properties of the sample suggest that the seasonal thermal regulation may be realized. The microstructure is fabricated following the geometry of the CPC 30-30. The deviation of the measurement from the simulation can be due to the three reasons: i) the height of the fabricated microstructure is about 80 µm while the theoretical design is about 90 µm; ii) shrinkages change the shape of the microstructure during polymerization for replication; and iii) the thickness of the deposited reflective material is insufficient and the light may directly transmitted through the reflective parabolic surface. In the future, rigorous parameters concerning the fabrication of microstructures, replication and deposition will be carried out, in order to minimize the deviation.

4. Conclusions

A novel glazing with embedded micro CPCs in a polymer layer which is attached to a glass pane is developped. A case study by simulation referring to seasonal thermal regulation due to the transmittance of direct solar light for Dubai shows that the novel glazing may reduce energy consumption in cooling and improve thermal comfort. The assessment of glare indicates that the novel glazing can reduce the risk of glare from 60% to only 20%. First samples with micro CPCs are fabricated, and the high transparency is achieved. The optical characterization using goniophotometer shows that the desired angular-dependent transmittance is obtained.

5. Acknowledgement

The authors would like to thank the Swiss Competence Center for Energy Research (SCCER) for funding of this project. The authors would like to show our gratitude to BASF Switzerland regarding the assistance for the preparation of samples.

6. References

1 Radhi, H. (2009). Evaluating the potential impact of global warming on the UAE residential buildings–a contribution to reduce the CO 2 emissions. Building and Environment, 44(12), 2451-2462.
2 Xing, Y., Hewitt, N., & Griffiths, P. (2011). Zero carbon buildings refurbishment—A Hierarchical pathway. Renewable and sustainable energy reviews, 15(6), 3229-3236.
3 Li, D. H., Yang, L., & Lam, J. C. (2013). Zero energy buildings and sustainable development implications–A review. Energy, 54, 1-10.
4 Bahaj, A. S., James, P. A., & Jentsch, M. F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. Energy and Buildings, 40(5), 720-731.
5 Lee, E. S., DiBartolomeo, D. L., Klems, J., Yazdanian, M., & Selkowitz, S. E. (2005). Monitored energy performance of electrochromic windows controlled for daylight and visual comfort. Lawrence Berkeley National Laboratory.
6 Scartezzini, J. L., & Courret, G. (2002). Anidolic daylighting systems. Solar Energy, 73(2), 123-135.
7 Rabl, A. (1976). Comparison of solar concentrators. Solar Energy, 18(2), 93-111.
8 Welford, W.T., & Winston, R. (1978). Optics of nonimaging concentrators. Light and solar energy. United States: Academic Press Incorporated,New York, NY.
9 Stine, W. B., & Geyer, M. (2001). Power from the Sun (2015, August 16): http://www.powerfromthesun.net/book.html
10 Kostro, A., Geiger, M., Scartezzini, J. L., & Schüler, A. (2016). CFSpro: ray tracing for design and optimization of complex fenestration systems using mixed dimensionality approach. Applied optics, 55(19), 5127-5134.
11 Rabl, A. (1976). Comparison of solar concentrators. Solar Energy, 18(2), 93-111.
12 Dubai: Annual Weather Averages (2017) http://www.holiday-weather.com/dubai/averages/
13 Demir, A., & Konan, A. P. D. N. (2013). Impact of Daylighting on Student and Teacher Performance. Journal of Educational and Instructional Students in the World, 1.
14 Sop Shin, W. (2007). The influence of forest view through a window on job satisfaction and job stress. Scandinavian Journal of Forest Research, 22(3), 248-253.
15 Reinhart, Christoph F., J. Alstan Jakubiec, and Diego Ibarra. "DEFINITION OF A REFERENCE OFFICE FOR STANDARDIZED EVALUATIONS OF DYNAMIC FAÇADE AND LIGHTING TECHNOLOGIES 2." Proceedings of Building Simulation 2013, IBPSA Conference, Chambery, France. 2013.
16 Kostro, A., & Schüler, A. (2017). U.S. Patent No. 9,695,629. Washington, DC: U.S. Patent and Trademark Office.
17 Kostro, A., Gonzalez Lazo, M. A., Leterrier, Y., Siringil, E., Hoffmann, P., & Schüler, A. M. (2015). Laser ablation and nanoimprint lithography for the fabrication of embedded light redirecting micromirrors. In Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale (No. EPFL-CONF-213287, pp. 15-20). LESO-PB, EPFL.
18 Kostro, A., & Schüler, A. (2017). U.S. Patent No. 9,695,629. Washington, DC: U.S. Patent and Trademark Office.
19 Kostro, A., Gonzalez Lazo, M. A., Leterrier, Y., Siringil, E., Hoffmann, P., & Schüler, A. M. (2015). Laser ablation and nanoimprint lithography for the fabrication of embedded light redirecting micromirrors. In Proceedings of International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale (No. EPFL-CONF-213287, pp. 15-20). LESO-PB, EPFL.