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Solar Concentrating Façade

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Abstract

The search for renewable energy sources is a wide area in which significant progress is still expected. This paper focuses on an energy system that uses Fresnel lenses to concentrate sunlight on a tubing system to heat up the working fluid. Fresnel lenses are lighter, thinner and cheaper to build than ordinary lenses. The model is designed to be integrated into the façade of a building that will then be heated or cooled using the energy extracted from sunlight. Details of the concept have been given in Tsoutsou et al. (2014) in which the viability of the concept was investigated and its energy saving and economic benefits have been quantified. A prototype façade of 1.5 x 3.6m, with 3 m² Fresnel lens area, has been constructed as a proto-type and tested in a standard office size of a dummy building. This paper presents the experimental performance of the solar concentrating façade and identifies advantages and disadvantages of the solar system. A model has been developed to predict the effect of design choices. This model is used to identify potential optimization strategies. In addition to the sun-tracking method, mass flow through the collectors can be adjusted to achieve maximum efficiency of the Fresnel collectors

Keywords

Building integrated solar collector, Building integrated solar façade, Fresnel solar collector, Concentrated solar collector

1 INTRODUCTION

The ambition of the European Union to develop more sustainable communities has resulted in defining targets to be achieved by 2020 and beyond. Such as the EU target set for 2030. The latter require at least 40% cut in greenhouse gas emissions compared with 1990; at least 27% of total energy consumption from renewable energy; at least 27% increase in energy efficiency. As reported in the Strategic Research and Innovation Agenda for Renewable Heating & Cooling from the Renewable Heating and Cooling Platform (Sanner et al., 2013), in 2010, heating and cooling accounted for 47% of the final energy consumption in the EU. This Platform has identified that 50% of the heating & cooling energy requirements could, by 2030, be generated by using renewable energy technologies. However, the contribution of renewable heating and cooling to the EU energy targets by 2030 and beyond will be determined by the availability of reliable, efficient and affordable technology. The Platform proposes to expand the market for solar thermal applications (among others) by achieving significant breakthrough through and developing more advancement in renewable heating and cooling technology. EU's Horizon 2020 indicates that nearly 40% of the final energy consumption takes place in houses, offices, shops and other buildings. This corresponds to 30% of the generated greenhouse gas emissions. The use of renewable heating and cooling and integrated solutions have been identified as key activities potentially with the biggest impact. The solar concentrating façade presented in this paper addresses these targets by developing reliable, efficient and affordable technology which can achieve these targets when implemented in an adequate scale. By implementing the proposed solar concentrating façade, the shell of residential or office buildings is used more efficiently to collect renewable (solar) energy. Systems using renewable energy, such as solar thermal systems in buildings, can be applied to cover water heating, space heating, cooling and other energy needs in order to achieve the above mentioned challenging targets.

Recently O'Hegarty et al. (2016) have reviewed and analyzed different solar thermal façade concepts. According to these authors novel solar thermal façade solutions include solar collectors integrated into balcony rails, shading devices, louvers, windows or gutters. Similarly to the Robin Sun solar thermal glass discussed by these authors, the proposed solar concentrating façade provides insulation, shading and a hot working fluid. This hot stream can be used to drive double-effect absorption chillers / heat pumps or directly be used for heating of the building or tap water. The proposed system consists of a double façade whereby it allows the sun rays to penetrate in the winter; while it minimizes the internal solar gains in the summer. Also Zhang et al. (2015) report on emerging building integrated solar thermal technologies and include the window-based active solar thermal façades which preferably make use of metal plates with a selective treatment as solar collectors and make use of a fluid circuit adhering to the absorber. These authors set the advantages of the solar thermal façade integrated into windows:

- If the renewable energy component is placed within cavity of glazing unit, it has no impact on life expectancy;
 - Regulating the visual relations inside/outside and the supply of daylight and passive solar gains;
 - High degree of pre-fabrication possible;
- The disadvantages have been considered as follows:
- Low light transmission through renewable energy components.
 - Additional moveable shading unit / element in clear vision area is necessary.
 - Potential risks in reducing the life expectancy of the solar panel include water leakage, thermal breakage and expansion due to high temperature.

Zhang et al. (2015) also only reported on the Robin Sun concept as solar thermal façade integrated within windows. They reported that optical efficiencies (collector's thermal efficiency with no consideration of the losses by convection and radiation) in the range of 0.70-0.90 and typical solar yields for domestic hot water of 669 kWh/m² which is the highest value for the reported technologies. The system uses evacuated tube collectors.

This paper focuses on a solar thermal system that uses linear non-imaging Fresnel lenses (FL) to concentrate sunlight on a tubing system in order to heat up a working fluid (WF). Fresnel lenses are lighter, thinner and cheaper to build than ordinary lenses. The system is designed to be integrated into the façade of a building, effectively extracting energy from the sunlight to use for heating or cooling purposes. The viability of such a system has been investigated and found to be of great potential. A simplified prototype has recently been built for which the efficiency and optimal mass flow can be analyzed. In this paper, a mathematical model of the system is introduced in order to identify its performance. Experiments have been conducted using the prototype in order to validate the model. The model is finally used to identify possible optimization strategies.

2 METHODOLOGY

The authors have designed and constructed a system in which the above listed advantages have been maintained while the disadvantages have been avoided as much as possible. This solar concentrating façade has then been built in a building to measure and assess its performance. It was necessary to quantify the effect of the Fresnel lenses (that function as shading elements) on the natural lighting of the building. The Fresnel lenses are translucent. In principle, they would marginally reduce the natural day light passing through the façade skin into the building. An identical façade without the solar collectors has been installed next to the solar concentrating façade that serves as a reference façade.

The Fresnel lens system (FLS) consists of 11 lenses whereby each lens focuses the sunlight on a heat collection element (HCE), the heat collector is an evacuated tube which contains copper tubes transporting the working fluid (WF). The total amount of energy absorbed by the working fluid, running through the copper tubes, depends on the transmittance of the Diamond Glass Sheet (which is the external pane), glass carrier of the FL and the evacuated tube, among other factors (Fig. 1).

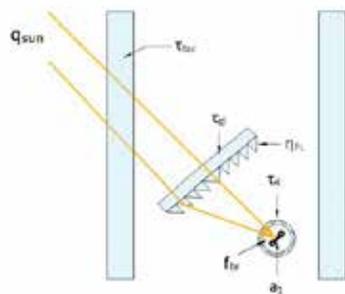


FIG. 1 View of the façade including the HCE. Left: schematic showing a single lens; Right: detail of the façade illustrating the transparency and shading effect of the façade.

The external Diamond glass sheet covering the FLS serves as the outer protective barrier to prevent environmental influences such as wind, dust, polluting particles and rain. These would have severe impact on the operation and performance of the system. The internal glass sheet inside the building, would serve as a safety barrier to prevent human interaction with the absorbing tubes. These contain a high temperature working fluid.

The external glass sheet is made of a High Grade, Ultra Clear transparent glass to maximize the transmittance of the sunlight. Even when this glass is used, not all of the solar energy incident on this glass, will penetrate the external pane and reach the Fresnel lens. The transmittance τ_{fac} accounts for the energy losses of the sunlight passing through the external glass sheet.

The FL converges incident sunlight on the façade onto the focus line HCE. The 11 Fresnel lenses of the system are composed of two parts that are laminated together. There are the actual lens and a thin layer of glass to increase robustness. Similar to the façade, this layer causes a loss of solar energy.

The HCE is the part of the system that absorbs the incident solar energy and transfers it into the working fluid (WF). The solar radiation incident on each of the 11 Fresnel lenses is focused onto its corresponding HCE. The WF absorbs the solar radiation while flowing through the absorbing tubes, entering in one tube and leaving through the other. The absorbing tubes are made of copper and are treated with a selective coating, which increases the absorptance for radiation in the solar energy spectrum and reduces the emissivity. The evacuated tube is made of glass with a high transmittance.

Apart from the heat losses of the FLS described in the previous section, some additional losses have to be accounted for. Firstly, the HCE are supported on one side by support brackets. It is very complex to determine the exact loss of energy these brackets induce, due to various parameters. Therefore, for developing a model of the Fresnel lens system (FLS), the heat loss in the support brackets will be considered as a fraction f_{br} of the total incident radiation. Since the energy losses in the FLS follow up consecutively, they can be multiplied to form a chain of losses. The total amount of energy absorbed by the absorber is given by equation (1):

$$q_{abs} = q_{sun} \times \tau_{fac} \times \tau_{gl} \times \eta_{FL} \times \tau_a \times a_1 \times (1 - f_{br}) \quad (1)$$

With q_{sun} the incident solar radiation perpendicular to the FL, τ_{fac} transmittance of the façade, τ_{gl} the transmittance of the glass layer on the η_{FL} the efficiency of the τ_a the transmittance of the glass envelope, a_1 the absorptance of the absorber and f_{br} the fraction of heat lost in the support brackets of the HCE. The FL are vertically aligned facing south and rotate around the HCE to keep the focal line on the absorber. The WF flows through the absorber tubes from the bottom to the top of the FLS and is heated gradually while moving up. The hot WF is then circulated through a test-loop so that the inlet temperature to the system is maintained at a fixed temperature. For different solar intensities, it is investigated how the total efficiency of the cycle can be maximized. The efficiency of the FL is obtained from Gupta (1981), the absorptance a_1 of the absorber is determined by using Norton (1992) and the fraction of heat loss f_{br} in the support brackets is determined by Tsoutsou et al. (2014).

A model is developed to determine the performance of the solar concentrating façade. The model is validated with experimental data so that realistic optimization studies and experiments can be executed. The model enabled us to identify the disadvantages listed in the proposed concept and finding ways to resolve them.

3 MODEL

The system model (MATLAB) is based on conservation of mass and energy and takes the specifications of the set-up and specifically of the FLS into account. The model inputs are the solar radiation q_{sun} , m_{wf} and the temperature of the WF at the inlet of the FLS, T_{wf_in} . To analyse the behaviour of the system, it is required to predict outlet temperature T_{wf_out} and the pressure drop as the WF passes the FLS. By changing the m_{wf} for different values of q_{sun} , it is possible to optimize the efficiency, defined as:

$$\eta_{solar} = \frac{m_{wf} \times c_{p_wf} \times (T_{wf_out} - T_{wf_in}) - W_{pump}}{q_{sun}} \quad (2)$$

The pumping power W_{pump} that is required to overcome the pressure drop in the FLS is obtained from:

$$W_{pump} = \frac{m_{wf} \times (p_{wf_in} - p_{wf_out})}{\rho_{wf} \times \eta_{pump}} \quad (3)$$

The impact of the geometry of the HCE on the performance of the FLS is determined through a numerical model. Energy balances are derived for each of the components of the HCE (Fig. 1), from which the temperature of the WF can be obtained:

$$q_{rad_1-4} + 2 \times q_{rad_2-4} = q_{conv_4-5} + q_{rad_4-5} \quad (4)$$

Where 1, 2, 4 and 5 are different parts of the absorber system, *rad* stands for radiation and *conv* stands for convection. Similar equations apply to identify the amount of incoming solar radiation that is conducted by the absorber or is radiated to other parts of the absorber system. The temperatures of the outer surface of the absorber tubes and outer surface of the envelope are first assumed and then iterated. With eq. (4) and similar equations, all other system temperatures can be calculated.

4 EXPERIMENTAL SET-UP

A 1.5 by 3.6 m prototype façade construction, with 3 m² Fresnel lens area, has been produced, installed and tested in a dummy building with standard office size, see right hand side of Fig. 1. The façade is orientated to the south.

The test set-up (Fig. 2) consists of a gear pump (B), gate valve (C), Fresnel lens system (FLS, A), a heat exchanger (HEX, E), bypass (F) and a storage tank (D). System boundary is selected around the first three components, because the focus of this research is on the efficiency of the FLS. The WF is a specific low viscous oil that can handle high temperatures and is pumped through the system counter clockwise with a controllable mass flow.

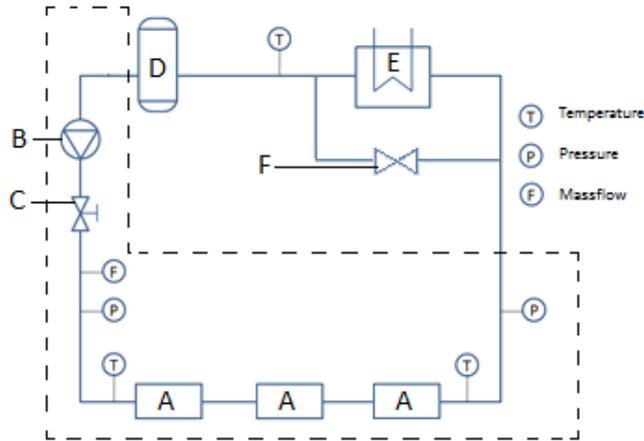


FIG. 2 Schematic overview of the experimental set-up

The experimental set-up measures the following data:

- 1) temperature of the WF entering the FLS, T_{wf_in} , temperature of the WF leaving the FLS, T_{wf_out} , temperature of the WF entering the storage tank, $T_{storage}$, temperature of the air surrounding the FL, T_{fac} ;
- 2) inlet p_{wf_in} and outlet p_{wf_out} pressure of the FLS;
- 3) volume flow, V_{wf} , of the WF;
- 4) the solar irradiance, q_{sun} , on a horizontal planar surface.

A Grant SQ2010 datalogger has been used to measure and collect data from calibrated thermocouples, pyranometer and a flowmeter. The thermocouples have an accuracy of ± 0.5 K and the pyranometer an accuracy of 10%.

During experiments the bypass valve was fully or partially closed in order to influence the temperature of the WF at the inlet of the FLS.

5 RESULTS AND DISCUSSION

Experiments have been carried out during a sunny partially cloudy day. This will enable to determine the dynamic effects (e.g. variation of solar irradiance) and impact on the performance of the FLS.

Based on experiment the heat absorbed by the working fluid Q_{abs_exp} is determined by eq. (5):

$$Q_{abs_exp} = \rho_{wf} \times V_{wf} \times c_{p_wf} \times (T_{wf_out} - T_{wf_in}) \quad (5)$$

This value is compared with the predicted value of the model Q_{abs_mod} . Results of this comparison are presented in Fig. 3.

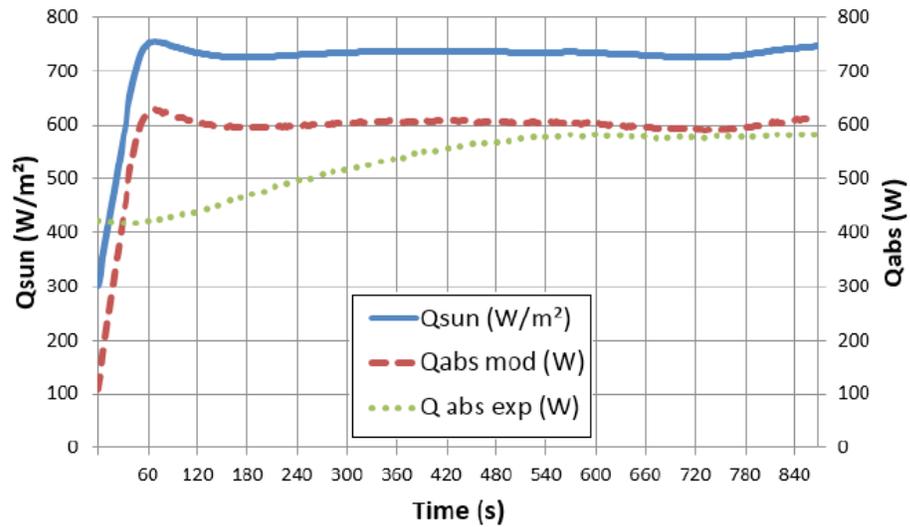


FIG. 3 Comparison of predicted and measured values of absorbed heat

Fig. 3 presents the measured solar irradiance q_{sun} , the predicted value of the absorbed heat Q_{abs_mod} and the value obtained by experiments Q_{abs_exp} . Results clearly show a convergence, between predicted and measured values after approximately 500 seconds. Fig. 3 also shows an initial large difference between predicted and measured values. Since a quasi-static mathematical model is applied, dynamic effects such as heat accumulation within the HCE are not taken into account.

The predicted pressure drop is validated by comparing the model results with the experimental data. The optimized m_{wf} , for two different values of T_{wf_in} , is depicted in Fig. 4. For every interval of values for q_{sun} , the m_{wf} leading to the highest efficiency is used. The maximum efficiency of the FLS for direct solar irradiance above 500 W/m^2 converges to approximately 30%.

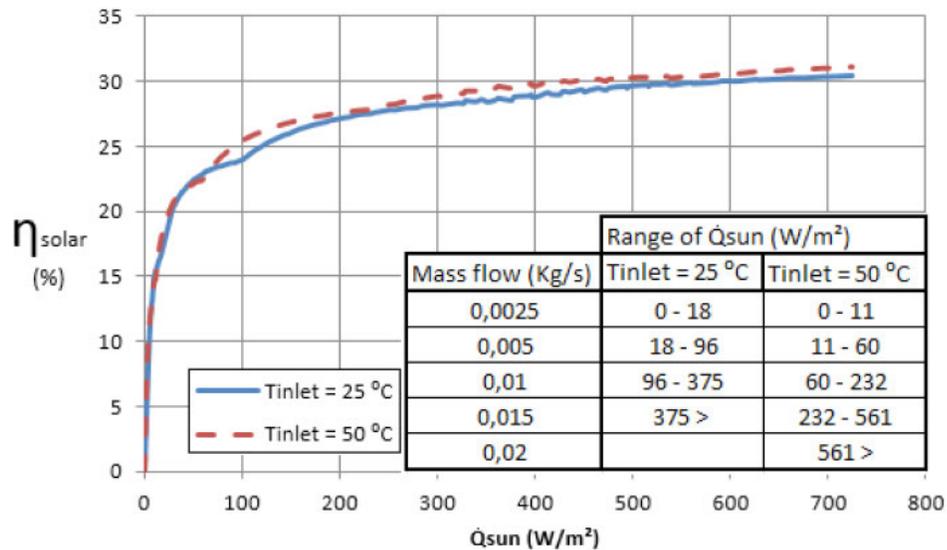


FIG. 4 System efficiency for optimized mass flows, plotted against variable solar radiation for $T_{wf_in} = 20\ oC$ and $T_{wf_in} = 50\ oC$.

The efficiency of the FLS can further be increased by minimizing the chain of losses. There are four main loss factors to be recognized here, namely losses in the façade, losses due to shadow, losses in the lenses and losses in the absorber tube.

5.1 LOSSES IN THE FAÇADE

The FLS has a façade that consists of diamond glass. The façade is used to protect the FLS from dust and rain and to minimize interaction with the environment to reduce losses. However, the transmittance results in significant losses through reflection and absorption. Eq. (6) shows the losses through the façade:

$$q_{fac} = q_{sun} \times \tau_{fac} \quad (6)$$

with \dot{q}_{sun} the radiation from the sun and τ_{fac} the transmittance of the facade. τ_{fac} is dependent of the angle of incidence on the façade, q_{fac} . Wide angles of incidence during the summer period ($\theta_{fac_min} = 61.5^\circ$ during summer solstice, the longest day on the Northern Hemisphere) are the reason a big part of the incoming radiation is reflected instead of being transmitted when the Sun reaches it's highest altitude. In winter, angles of incidence are always small, ($\theta_{fac_max} = 49.5^\circ$ during winter solstice, the shortest day on the Northern Hemisphere). This phenomenon is displayed in Fig. 5. In Fig. 5 one can see the difference in efficiency of the façade throughout the year. Around the beginning of spring (day 80) and autumn (day 264) the Sun's radiation has the ideal combination of a relatively high energy density and relative low angles of incidence. During these two periods the amount of energy that passes the facade is higher than in summer although the total irradiance as measured in the Netherlands is significantly higher, during summer as shown in Fig. 5.

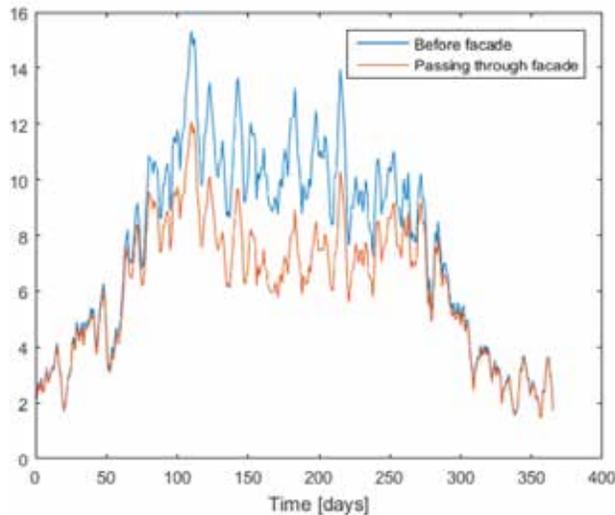


FIG. 5 Irradiance compared to total energy passing the glass façade.

Fig. 6 shows the efficiency of the façade throughout a year. Since the FLS is attached to the façade of a building facing south, it is not possible to make use of the morning and afternoon sunshine during summer, because during early morning and late afternoon the azimuth is bigger than 90°. From Fig. 5 and 6 it follows that the glass façade has a huge influence on the performance of the system but that this loss factor cannot be reduced without changing the fundamental assumption that the FLS has to be attached to a building.

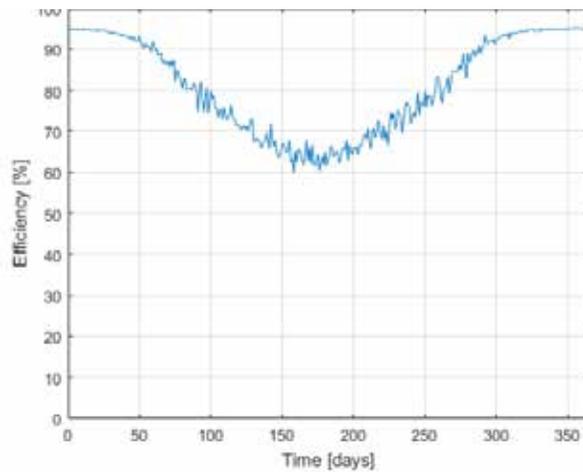


FIG. 6 Efficiency variation of the glass façade during one year.

5.2 LOSSES DUE TO SHADOW EFFECT

There are two things that cause shadow on the lenses in the current FLS. The first cause is the frame of the system. During early mornings and in the late afternoon, a high azimuth sun causes shadow on the sides of the lenses. To counter the negative effect of this shadow, a mirror can be placed on the inside of the frame. From the law of reflection it follows that the angle of reflection and angle of incidence are both equal to the angle of incidence of the sun and that the distance from the lens to the façade is on both sides equal because the lens is aligned parallel to the façade.

The second cause of shadow on the lenses is overlap. Because the lenses follow the elevation angle of the sun, they will face upwards during solar noon. The Matlab calculations show that the total area of the lens in the shadow is significant and reaches a maximum of 42%, at which point the top lens is shaded for 92% by the aluminum frame and the other lenses for 36% because of overlapping lenses. This is unfortunate, because the shadow caused by overlap is the biggest when the irradiance is the highest. Because the value of the irradiance is measured in a plane perpendicular to the irradiance, the useful area of the façade is also perpendicular to the radiation. Because the frontal area of the façade is constant, it becomes clear that useful area is only dependent on the trajectory of the sun. When there is shadow on the lenses, it means they overlap and no radiation from the sun can pass between the lenses. When no sun rays can pass between the lenses, it means the maximum surface is irradiated by the sun. Calculations show that for an elevation angle of more than 45.6° shadow starts to appear on the lenses, so for lower elevation angles some sun rays fall between the lenses and through the FLS in the building. After establishing that the total irradiance on the collector throughout the day increases with decreasing elevation angle, one could argue that it is best to have no shadow on the lenses when the elevation angle is 0 and for higher have shadow on the lenses. However, this poses questions to the losses in the absorber and the cost-efficiency. Optimizing the amount of lenses and their width to improve the overall efficiency is being investigated for the improved design of the solar concentrating façade.

5.3 LOSSES ON THE LENSES

Between a light beam reaching a lens and reaching the absorber, intensity is lost due to mainly two factors: incorrect projection on the absorber and reflection on the surface of the lens (similar to what has been discussed for the glass protection of the FLS).

The requirement to extract the maximum amount of energy from a solar beam is that every solar beam, projected on the lens, has to be projected on the collector as well. In this section the projection area is defined as a function of the angle of incidence on the lens, θ_l . As a result of the blocking effect and off-axis aberrations, the lens always has to be directed perpendicular to the height of the sun with a maximum deviation of 6° (Tsoutsou et al., 2014). The current system is able to follow the height of the sun very closely. As a result the elevation angle has no effect on the position of the projection area. The azimuth of the sun has an effect on the projection area. Because the angle of incidence is a combination of the elevation angle and the azimuth, and the lenses are always lined up with the elevation angle, the angle of incidence on the lens θ_l is equal to the azimuth of the sun. The movement of the projection area along the collector is calculated by using the law of Snellius in combination with eq. (7).

$$x_{pro} = \delta \times \tan(\theta_{int}) + f \times \tan(\theta_l) \quad (7)$$

Where δ is the thickness of the lens, θ_{int} the internal refraction angle of the lens, f the distance between the lens and collector and x_{pro} the position of the projection area along the collector. During solar noon the azimuth is 0° and therefore x_{pro} is 0, which means the projection falls precisely on the entire collector. When the azimuth is unequal to 0 the projection shifts to one side and as a result one end of the projection does not fall on the collector. It becomes clear that in the current system a significant part of the projection area does not fall on the collector during early morning and in the evening. The only way to prevent these losses and have the projection fall on the collector, is to make the position of the collector dynamic. Mirrors on the side of the facade can also help prevent these losses.

The second effect of the azimuth is a changing focus distance perpendicular to the lens. When the azimuth is high the focus distance becomes smaller and a wide and diffuse projection area is created where the collector is currently positioned. Because of the changing focus distance, the actual size of the projection area at the position of the collector varies greatly. Because the collector size is constant, the distance between collector and lens is the only variable to match the projection area and collector. This problem can be solved by making the tracking system 2-D which is under consideration in the new design of the solar concentrating façade.

6 CONCLUSIONS

Experiments executed with a prototype solar concentrating façade have indicated that most of the advantages of window-based active solar thermal façades as reported by Zhang et al. (2015) apply for the present design:

- since the double-façade is air-tight, wind, dust and rain cannot deteriorate the system;
- the FLS allow diffuse light to penetrate the working space so that the day-light penetrates sufficiently in the room;
- the double-façade can be produced in a factory and easily installed on-site;
- the present configuration functions as complete shading so that no additional shading is needed;
- the working fluid operates at low pressure reducing the risk of pressure failure.

Unfortunately its experimental solar efficiency is relatively low. An analysis of the different losses that take place in the solar collector has identified a number of causes for this level of efficiency. Investigation of these losses has indicated possible methods to improve the prototype. A large number of these effects is being implemented in a second prototype which is presently under development.

Acknowledgements

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