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First results from a Linear Mirror II system with a solar-air heat exchanger

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We present first measurements with an innovative solar-air heat exchanger illuminated by the concentrated light of a Linear Mirror II system at air temperatures up to 230 °C. The surface of the heat exchanger is, respectively, selective to direction and position of light absorption and emission. The system is controlled by a Siemens Logo PLC, so that it can be inserted into the IOT.

Introduction

In many countries already a relevant fraction of electric energy is provided by renewable energy sources, mostly photovoltaic, wind energy and hydro energy [1][2]. In comparison, the contribution of renewable energy sources to thermal energy consumption is much lower, in spite of the fact, that industry as well as private homes consume more thermal energy than electric energy [3]. As a consequence, new and improved systems for providing renewable heat energy become a necessary condition for further reducing the level of CO2 production.

These new technologies must provide thermal energy at elevated temperatures also in winter, also at northern latitudes and in a simple and economic way. The Linear Mirror technology was developed to meet these requirements [4] : in its standard version, the Linear Mirror provides hot water at temperatures up to 100°C also in winter, and at a rather high efficiency, due to the low specific heat of its absorber [5]. The limit of 100°C is applied by the control software in order to ease the integration of the Linear Mirror into existing heating systems.

The Linear Mirror can also be used to provide higher temperatures as well – for example, during an experiment for producing biochar from simple biomasses using only solar energy (“solar carbon”), a temperature of up to 500 °C was reached [6].

In order to use water as a heat carrier at temperatures above 100 °C, high pressure installations are necessary, which tend to be complex and expensive and may create security problems. In addition, transferring the heat from the pressurized water to the application process may be difficult and inefficient. For instance, it would be difficult to torrefy or pyrolyze cheap biomasses by means of hot water - rotating drums or similar devices would be needed, or additional water-air heat exchangers [7].

It would be simpler, if one had a flow of hot air available. Then one could roast cheap biomasses in the same way as coffee is roasted, which is a cheap and simple procedure. Unfortunately, for roasting coffee, the hot air is provided by a gas flame, which is not CO2 neutral. It would be of great advantage to have a solar-air heat exchanger available, which can produce hot air from concentrated sun light.

Requirements for a high temperature solar-air heat exchanger

The selective absorbing surface is an important element of solar heat exchangers:. the heat exchanger must, at the same time, absorb sun light well instead of reflecting it - and must emit as little thermal radiation as possible. It should consequently have a high absorptivity for sun light and a low emissivity for thermal radiation [8].
According to Kirchhoff's law of thermal radiation, the absorptivity and the emissivity of a surface are equal, but not in a global sense, rather they will be functions of the wavelength of the electromagnetic radiation and also of the direction of the photons [9].
Selective absorbing surfaces make use of this fact: they have a high absorptivity (and emissivity) at the wavelength of the incident sun light, and a small emissivity (and absorptivity) at the much larger wavelength of the thermal radiation, emitted by the surface.
For example the standard absorber used for heating water with the Linear Mirror (made by the company Energie Solaire (Switzerland)), is equipped with this kind of surface. Unfortunately, its selective surface would not withstand high temperatures, and therefore cannot be used to heat air to high temperatures.
This led to take into account two aspects: 1. whether we can construct a solar absorber that doesn't need any specific surface treatment but has selective properties thanks to different mechanisms where the selectivity of the absorber doesn't necessarily need to refer to wavelength; 2. the heat transmission coefficient is very low for air, therefore the solar-air heat exchanger must have a large surface

In the next chapter we describe, how these two requirements – first a selective surface, second a large surface - can be combined into a very simple solution.

Basic properties of the Isomorph solar-air heat exchanger

Our solar-air heat absorber is made of stainless steel plates, arranged in a bellow shaped structure, as shown in figure 1, so that incident light rays undergo multiple reflections. In each reflection the light ray looses part of its energy, heating the surface.

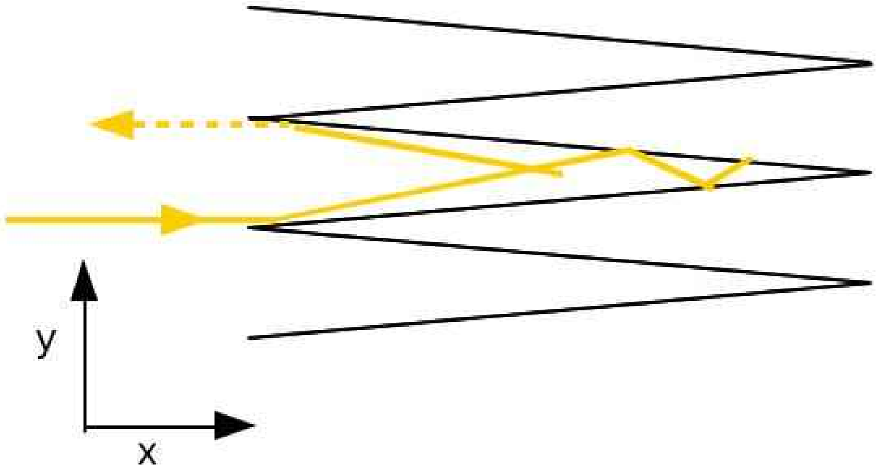

Figure 1: an incident light ray (orange, solid line) undergoes multiple reflections on a metallic surface, until it finally bounces back (dotted line), each reflection reduces the light intensity. Not all reflections are shown in the figure.

For instance, if a light ray in figure 1 enters parallel to the horizontal x-axis, and if the opening angle between the plates is 10°, and assuming an absorptivity of a=0.2 the light ray will be directed away from its original direction by an additional 10° from each reflection. It will therefore undergo 18 reflections and travel back in the horizontal direction, and its intensity will be reduced by a factor of $(1-a)^{18} = 0.02$.

More in general, if we relate the incident intensity I_{inc} with the reflected intensity I_{ref} (after n reflections) by means of the effective reflectivity r_{eff}, $I_{ref}=I_{inc}\cdot r_{eff}$ where the effective reflectivity results from n reflections with the characteristic factor of reflection of the surface, r, $r_{eff}=r^n$ and with the effective absorptivity a_{eff} , we find $a_{eff}=1-r^n$

We next compare the intensity emitted by the heat radiation into the very direction of this incident ray and at the same spatial position. This is exemplified in figure 2, where we show heat radiation emitted into the direction of the incident light of figure 1.

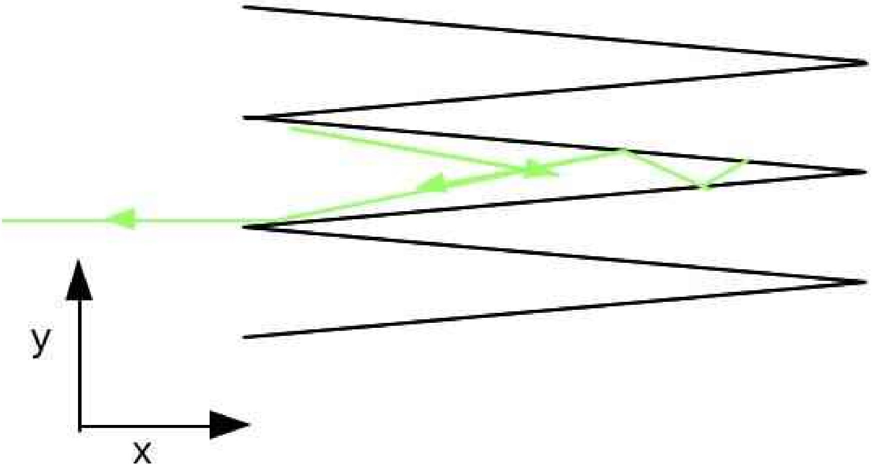

Figure 2: radiation emitted into the direction of the incident light in figure 1, and at the same position. An observer in this direction will see not only the light emitted from a surface element directly, but also the reflection of light rays emitted at other positions, as indicated in this figure (as in figure 1, not all ray elements are shown.)

The radiation emitted in this direction has several components: there is direct radiation emitted from the surface; there is also heat radiation which is reflected once, or twice etc, before being emitted into this very same direction at the same position. The geometric situation is identical between figure 1 and 2.

With the black body radiation emitted directly from the material I_b, the radiation, which directly results from the emission of the surface, without having been reflected, has intensity $I_0=I_b\cdot e$ while the intensity contributions from radiation, which has undergone k reflections will be $I_n=I_b\cdot e\cdot r^k$ for a total of $I_{tot}=\sum_{i=0}^{k} I_b\cdot e\cdot r^i$, which is the geometric series. The ratio between the total emitted intensity and the black radiation intensity is the effective emissivity by definition, $e_{eff}=I_{tot}/I_b$ and so the evaluation of the geometric series amounts to $e_{eff}=\frac{e\cdot(1-r^{k+1})}{1-r}=1-r^{k+1}$

When we compare the two expressions $e_{eff}=1-r^{k+1}$ and $a_{eff}=1-r^{n}$ we need to take into account, that by its very nature the geometric series has a particular counting convention, as is shown in figure 3 with an example.
In figure 3a the incident light is reflected twice, so n=2. In the corresponding figure 3b the emitted light is described by k=1, so that k+1=2 which is equal to n, for k+1=n.
Therefore, the effective absorptivity, a_{eff} , and the effective emissivity, e_{eff} are again equal, but are much different from the material properties, a and e, of the metallic surface.

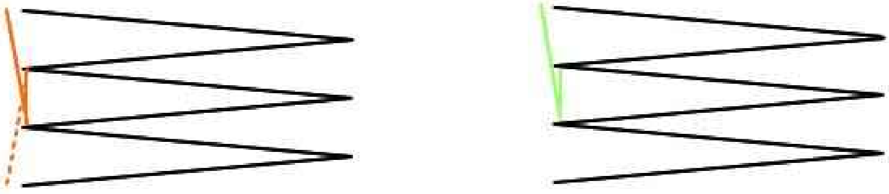

Figure 3: left: a light ray incident at a large angle (solid line) is reflected twice before emitted from the absorber (dotted line). Right: a ray from thermal radiation emitted with the same spatial and directional parameters as the incident light ray (shown in the left part of the figure), only in the opposite direction.

It is now clear (and it can also be seen for example from a comparison of figure 1 and 2 with figure 3), that the number of reflections respectively depends on the angle of incidence or emission.
Therefore, a_{eff} and e_{eff} depend on the angle with respect to the x-axis: radiation absorbed or emitted at a large angle will have an associated absorptivity or emissivity, which is small, when compared to radiation which has an a direction close to the x axis.
The concentrated light from the Linear Mirror incident on the heat exchanger has a direction close to the horizontal (x axis in figure 1). It will be absorbed very well, though the surface of the absorber consists of reflecting stainless steel. The thermal radiation emitted from the hot surface instead will be emitted into all directions – on average it will be emitted with a low emissivity.
Our heat exchanger has therefore selective properties – it absorbs well sun light while at the same time emitting little thermal radiation, the process depending on wavelength, rather than on directionality.

There is a second effect, which presumably increases the performance of this absorber: for a given direction of incidence, the number of reflections of a light ray will always be the same, regardless of where it first hits the surface. The density of these reflections instead will very much depend on the initial point of incidence. Rays incident close to where the walls of the bellow meet will deposit most of their energy in a very small spatial region. The steel there will correspondingly become very hot. So even if the incident radiation is distributed uniformly in the y-direction, the surface will not show a uniform temperature at all: it will be hottest in a region, which supposedly is relatively well protected against heat loss to the environment.
The discussion in this chapter is obviously in first approximation and a computer simulation would be needed to discuss in depth, for instance taking into account the fact, that not all of the light reflected by a surface will be reflected according to the law of reflection, some diffuse reflection will be present as well.

Basic design of the solar-air heat exchanger

A drawing of the resulting device is shown in figure 4: behind the metallic bellow structure there is a flow of air of variable speed, heated by the hot metal surface. The heat exchanger can be operated as part of a closed circuit, for instance it could be operated under pressure in future versions of the device.

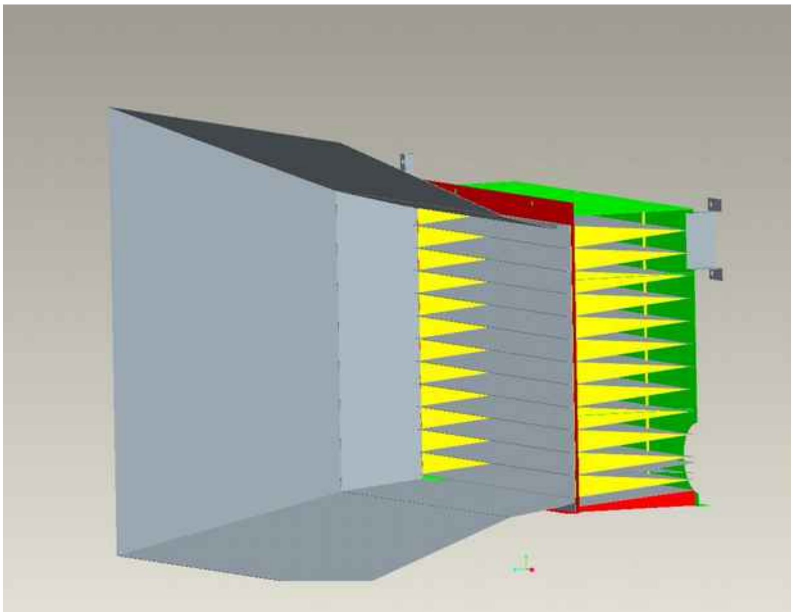

Figure 4: side view of the solar-air heat exchanger. The bellow structure is in contact with a flow or air. A secondary mirror directs stray light onto the absorber surface and protects the absorber surface from ambient wind.

The bellow structure – which is receiving the concentrated light from the Linear Mirror - is 70 cm wide and 54 cm high. Since the Linear Mirror II has an aperture area of 13.8 m^2, the mean concentration factor is $13.8/0.7 \cdot 0.54 = 36$. The bellow structure is surrounded by a secondary mirror, which protects the heat exchanger against wind as well.

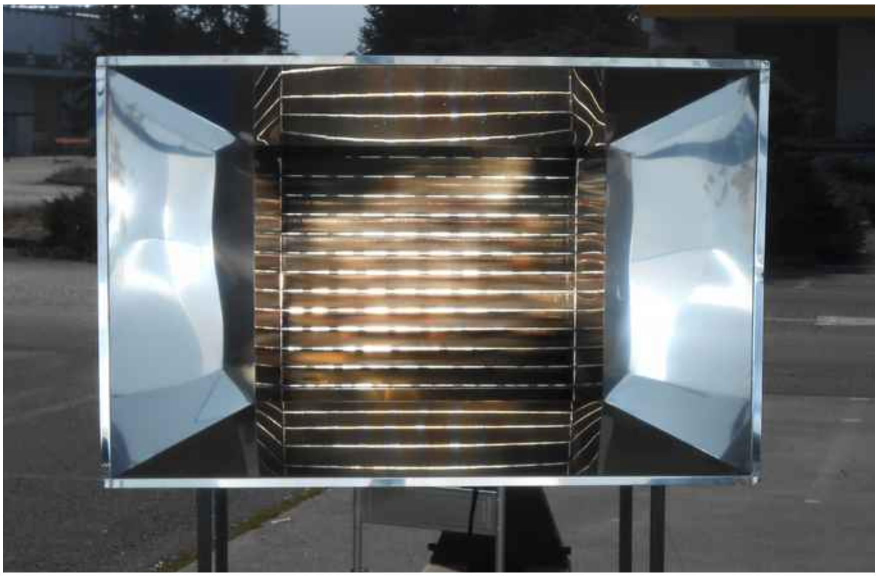

Figure 5: the solar-air heat exchanger illuminated by the concentrated sun light from the Linear Mirror II system.

First Results

This research does not aim to produce a detailed study of its performance as done, for instance, in the Solar Keymark measurement context, it rather aims to verify whether this new kind of device can be useful for practical applications.

In figure 6 part of the solar-air heat exchanger (figure 5) is covered for a comparison with the solar-air heat exchanger (produced by Energie Solaire), normally used in the standard version of the Linear Mirror for heating water. (In the photograph of figure 6 the secondary mirror was removed.)

Figure 6 confirms that, as expected, the new solar-air heat exchanger reflects very little of the incident concentrated sun light.

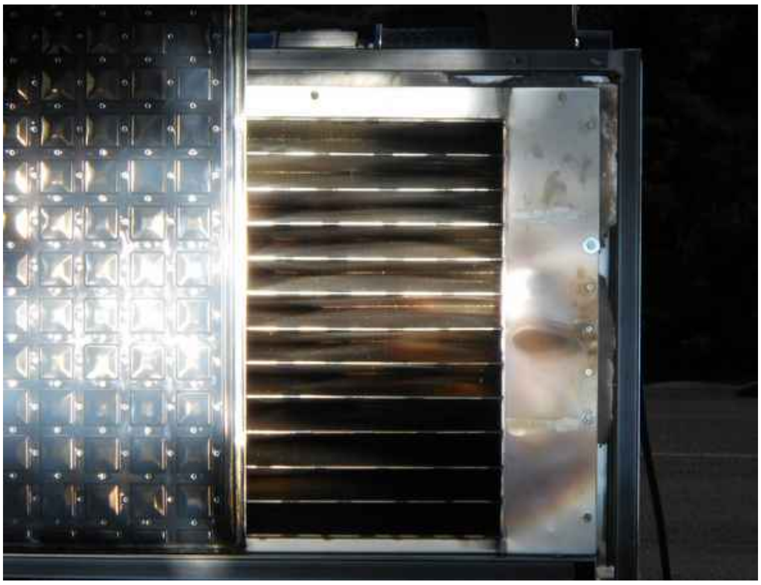

Figure 6: comparison between a conventional heat exchanger with wave length selectivity (left) to the new solar-air heat exchanger.

The heat exchanger was exposed to the concentrated sun light on a sunny day (12.3.2019) with a ventilator pushing a flow of ambient air through the heat exchanger. The flow was measured using a hot wire anemometer. Both the ambient temperature and the temperature of the hot air exiting the heat exchanger were measured. The heating power of the device was calculated from the temperature difference and the flow.

The thermal power as a function of air temperature is shown in figure 7. Figure 7 shows, that the power provided by the solar-air heat exchanger diminishes by only about 10% between 100 °C and 230 °C, which consequently makes this kind of solar-.air heat exchanger a useful device for applications up to that temperature.

Also the quantity of heat energy harvested with this device is quite remarkable, for instance at a temperature of 80 °C it provides almost 9 kW on a sunny day, which is about as much as the conventional solar-water heat exchanger provides at this temperature.

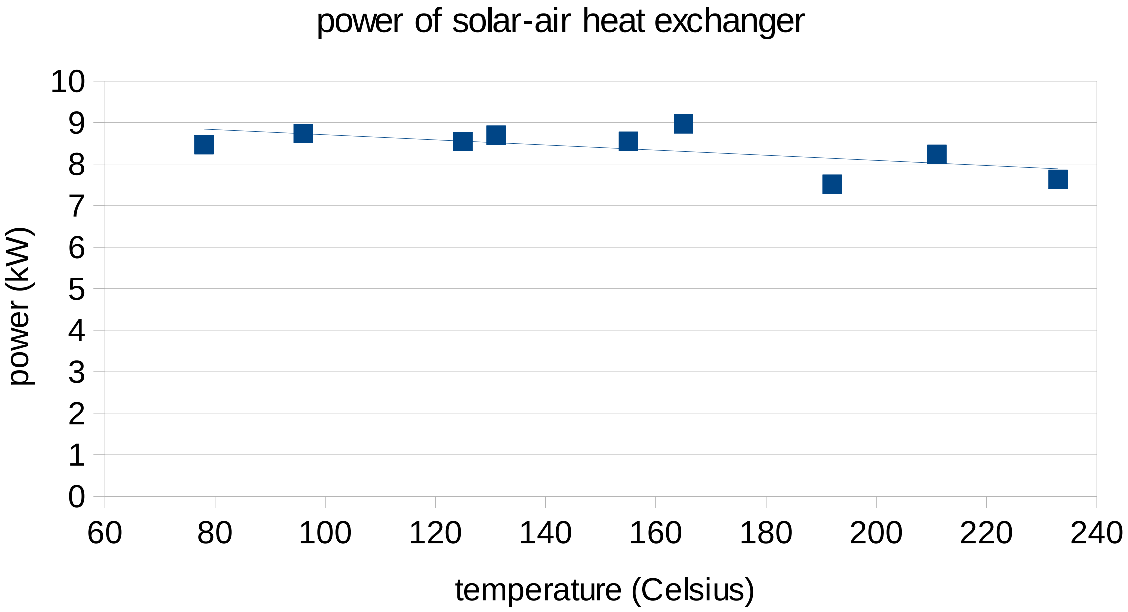

Figure 7: thermal power of the solar-air heat exchanger operated with the Linear Mirror II system.

The Linear Mirror as element of the IOT

Hot air from solar energy can be used for many different applications, not only for heating buildings, but also for providing energy for industrial processes, for instance the torrefaction of biomasses, solar cooling, or for producing pressurized steam for electricity production.

We note in particular, that the efficiency of the solar-air heat exchanger, as evidenced in figure 7, can be still increased by means of a higher solar concentration factor – the Linear Mirror is made in a modular way, additional mirrors could thus be installed, which increase the light concentration. In that case, temperatures well above 230 °C might also be possible, being limited only by the optical and mechanical properties of steel.

The Linear Mirror with its solar-air heat exchanger could therefore be used for dedicated purposes at different times, in function of the actual needs of the consumer. For instance one and the same device could be used in winter for heating, in summer for cooling and at other times for providing process heat. In to achieve this, the Linear Mirror must communicate with the internet, so it must be part of a smart grid as element of the internet of things (IOT).

In the past, the Linear Mirror was controlled by electronics, which we had developed ourselves (Isomorph srl), because when the development of the Linear Mirror started (about 10 years ago), cheap and versatile industrial computers were not yet available. Isomorph electronics was able to communicate with the internet, but it did not follow nowadays industrial standards.

We have therefore created a new version of the control software, which runs on the Siemens Logo PLC, including a solar tracker.

Since the Logo is a web server as well, the Linear Mirror can be used as an element of the IOT, interacting with other other components, with meteorological informations and other input messages.

Conclusions

The Isomorph solar-air heat exchanger has an absorber surface, which is selective with respect to the direction of incident and emitted radiation – while instead conventional heat exchangers are selective with respect to the wavelength. In a first test, this heat exchanger behaves about as well as the conventional solar-water heat exchanger with wavelength selective surface, normally used in the standard version of the Linear Mirror. Furthermore it allows to reach much higher temperatures, in our first test 230 °C were reached without problems.
The solar-air heat exchanger was obtained from fundamental general physics considerations, not from a detailed computer simulation, we therefore expect that it can be further improved in the future. Already now this new solar-air heat exchanger, together with the Linear Mirror opens many new applications to solar thermal energy.

Acknowledgement

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