SOLAR OVEN WITH HEAT-PIPE VACUUM TUBES FOR EASE OF ARCHITECTONIC INTEGRATION

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1. Introduction

Solar ovens are devices that are expected to operate for several hours without constant attention of human operator. Reflective surfaces are often used to increase the amount of radiation collected by the oven, but in this case frequent reorientations would be needed to compensate for the sun displacement. This is one of the main problems when trying to integrate them as a fixed part of a existing construction.

Instead of using reflecting flat or parabolic surfaces to make an optical concentration, vacuum tubes can be used to collect radiation and introduce it into the insulated oven cavity where it is stored.

Vacuum tubes are usually employed in hot-water solar collectors in cold climates to minimize heat losses, so they meet the requeriments of good insulation and resistance to high temperatures that are also necessary for the design of solar ovens. In particular, heat-pipe vacuum tubes can transfer heat without the presence of an external circulating fluid (like water or oil).

Solar ovens with vacuum tubes offer some advantages over reflecting surfaces, like a high tolerance to azimut and elevation of sun, what is very important when the device should operate for a long time without constant attention of human operator or cannot be reoriented. Moreover, vacuum tubes can be placed in vertical position without significant loss of performance.

This paper is dedicated to the design and construction of a solar oven with vacuum tubes that can be easily integrated in new or existing buildings, in particular rural houses in remote areas or developing countries.

A prototype of this solar oven has been developed and tested under different positions and orientations of vacuum tubes to achieve the maximum performance.

Fig. 1 shows one of the preliminary test of the vacuum tubes used in the oven.

Fig. 1: First experiments of solar owen with vacuum tubes

2. Oven design criteria

There are numerous precedents in the literature of the use of vacuum tubes for applications different from the heating of domestic hot water (Balzar 1996, Esen 2004, Gradinetti 2011, Kee 2007, Khalifaa 1986, Kundapur 2011).

This article describes a low cost oven that can be integrated into an existing or new construction and does not require access to the outside for use or adjust. It should be easy to use for people without specific training like in many rural areas or developing countries.

A vertical configuration has been chosen for several reasons:

- Ease of placement on a wall of an existing construction
- heat pipe vacuum tubes need a certain angle of elevation for the internal fluid to circulate properly
- vertical position tends to equalize benefits in winter and summer, as the collector works better with low sun elevations

Although the idea is to build a permanent and fixed oven, the prototype is made with a portable design to allow for position changes and modifications.

The prototype has been designed in two separate pieces (tube holder and oven) to test different configurations and materials (wood, glass, plastic, insulations of different types) and divide the system into hot and cold zones to replace parts if damaged.

The lower part of the oven serves also as storage of replacement tubes and protection for transport.

The lower part of the oven has two rows of tubes. The tubes in the front row are the main collector of the oven. The tubes in the back are intended only as a replacement, but serve also as thermal mass and may capture some radiation.

3. Heat-pipe vacuum tubes

Vacuum tubes meet the requeriments of good insulation and resistance to high temperatures that are necessary for the design of solar ovens. In particular, heat-pipe vacuum tubes can transfer heat without the presence of an external circulating fluid (like water or oil). Heat-pipe vacuum tubes used in this prototype have the following characteristics (Jiangsu, 2011):

- length 1800mm, outer diameter 58mm, absorber diameter 47mm.
- Glass tube: reflectance: 7.5%, absorbtance: 1.8%, tranmittance (two layers): 80%
- Absorption coefficient: ≥0.93, Emissivity: ≤0.08
- Starting temperature: ≤25 ºC Max.temperature: 250 ºC

According to tests carried out for spanish regulations (BOE, 2010), a collector with 10 tubes of the same type have the following characteristics:

- absorber area of each tube: 0,081m^2
- output power (Tm-Ta=0ºC, 1000W/m^2): > 581W
- output power (Tm-Ta=60ºC, 1000W/m^2): > 454W

With this data the area of a 3 tubes collector is 0,243m^2, equivalent to a typical box oven with a glass window of 0,6x0,4 m^2 area.

4. Collector design

As a starting point for the design of the oven it has been chosen a collector area equivalent to a conventional box solar oven with a glass window of 0,6x0,4 m^2. As the absorber area of a single tube is 0,081 m^2 at least 3 tubes should be used.

The tubes will be placed in vertical position for the requirements of architectonic integration. This point will be discussed in next paragraphs.

The distance between the tubes should be enough to avoid shadowing between them. If the distance between tubes is the same as its diameter (58 mm), sunrays with an azimut of 60º will not produce shadows (Fig 2). For an angle of 45º a distance of approximately half a diameter can be allowed. For the prototype a distance between tubes of a whole diameter has been chosen.

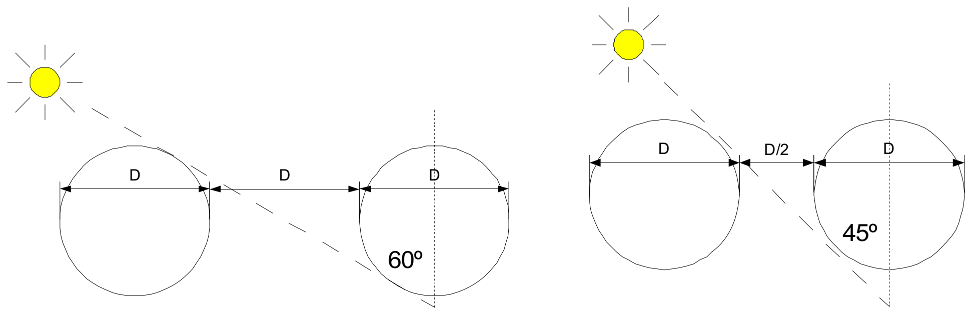

Fig. 2: Separation of tubes and effect on shadowing

The cylindrical shape of the absorber and its vertical position make the collector area does not vary significantly with azimuth during maximum solar insolation hours, so it is not necessary to reorientate.

Rear reflectors can be added to improve radiation collection. In summer reflectors help to compensate for the higher elevation and in winter for the lower insolation. Reflectors also improve insulation and reduce heat losses.

As mentioned above, collector tubes are placed in vertical position for architectonic integration. This position is not the typical of a solar collector, so some calculations have been made to determine its performance. Fig.3 shows the daily solar radiation at Nigran (Galicia, Spain, latitude 42ºN) during year 2005 for an horizontally oriented photovoltaic cell (orange) and a vertically oriented photovoltaic cell (yellow). As seen in this figure, vertical position gets much better results in winter days and worse in summer.

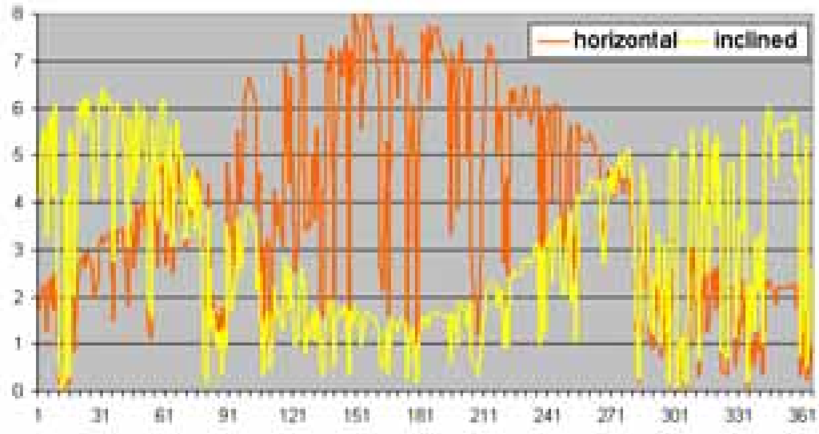

Fig. 3: Daily solar radiation in Nigran during year 2005 (Kwh/m^2)

This results can be represented in terms of gain between vertical and horizontal positions. Fig. 4 shows a comparison between them. For the vertical position in winter there is a gain of 2.5 and in summer there is an attenuation of 5.

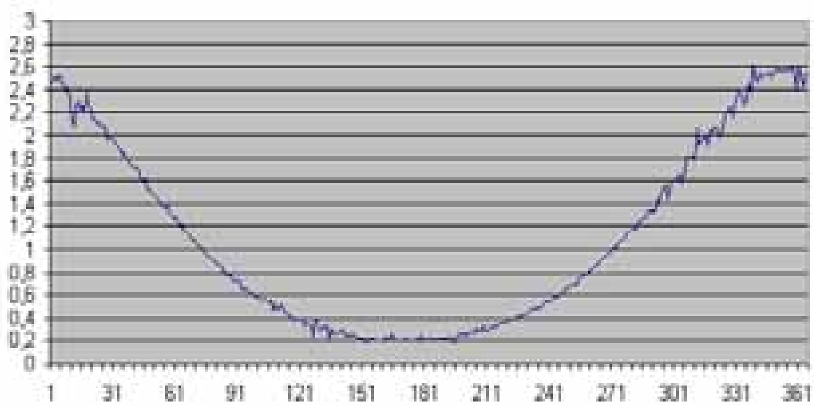

Fig. 4: Comparison of vertical and horizontal position of collector

Therefore it can expected that the oven works better in winter than in summer, and in the early hours of the day better than at noon. To compensate for the attenuation in summer it could be necessary increase the size of collector (number of tubes) to assure performance in all days and circunstances.

5. Oven construction

5.1. Structure of the oven

- The structure of the oven is made of weatherproof plywood (also known as WBP or phenolic plywood). This type of material can resist temperatures of 100ºC (boiling water) or more. If the oven reached higher temperatures the upper part of the structure should be made of a different material.
- The whole structure can be made of a single piece of plywood of 2.44x1.22m^2 as seen in Fig. 9.
- The oven frame is divided into two pieces, tube holder and oven. Fig. 5 shows the lower and upper part of the structure.
- The upper part forms the oven cavity, and the lower holds the vacuum tubes.
- The lower part of the oven has two rows of tubes. The tubes in the front row are the main collector of the oven. The tubes in the back are intended only as a replacement, but serve also as thermal mass and may capture some radiation.
- The front row of tubes is designed to hold 3 or 5 vacuum tubes to increase power.
- When not in use, the lower part of the oven serves as an storage and protection to avoid breakage of tubes.

Fig. 5: Oven structure: lower part (left) and complete assembly (right)

5.2. Thermal transfer structure

- This structure connects the heat-pipes evaporators with the heat diffuser inside the oven cavity. It must be made of a high conductivity material, like copper tube.
- The coupling of the evaporators can be made by a short piece of copper tube with a longitudinal slot Fig. 6 shows a detail of the structure and Fig. 7 shows the complete assembly wihout the diffuser.
- The heat diffuser can be a rectangular piece of copper painted in black. This piece must be soldered to the copper tubes of joined with thermal silicone to improve heat transfer.
- The upper part of the vacuum tubes must be well protected to avoid breakage. It must also be well insulated since this is the maximum temperature point of the oven.

- All the internal surfaces of the oven must be covered with a infrared reflecting material, like aluminium foil of polyester film.

Fig. 6: Copper tube structure

Fig. 7: Thermal structure assembled

5.3. Vacuum tubes support

- Coupling between vacuum tubes and oven support is a very critical point of the design because of the high risk of breakage of tubes.
- It must be made of soft materials that can absorb shocks during movements or transportation.
- The lower end of the vacuum tubes is extremely fragile and must be well protected.
- In this prototype coupling of the tubes to the structure has been made with polypropylene cups as seen in Fig. 8.

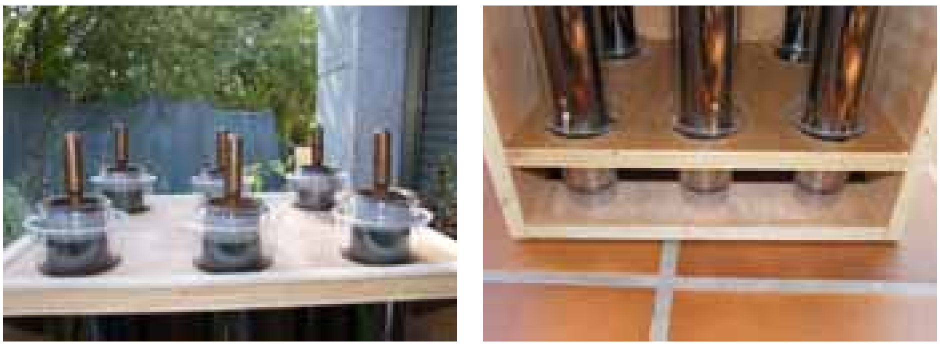

Fig. 8: Vacuum tubes support made of polypropylene cups

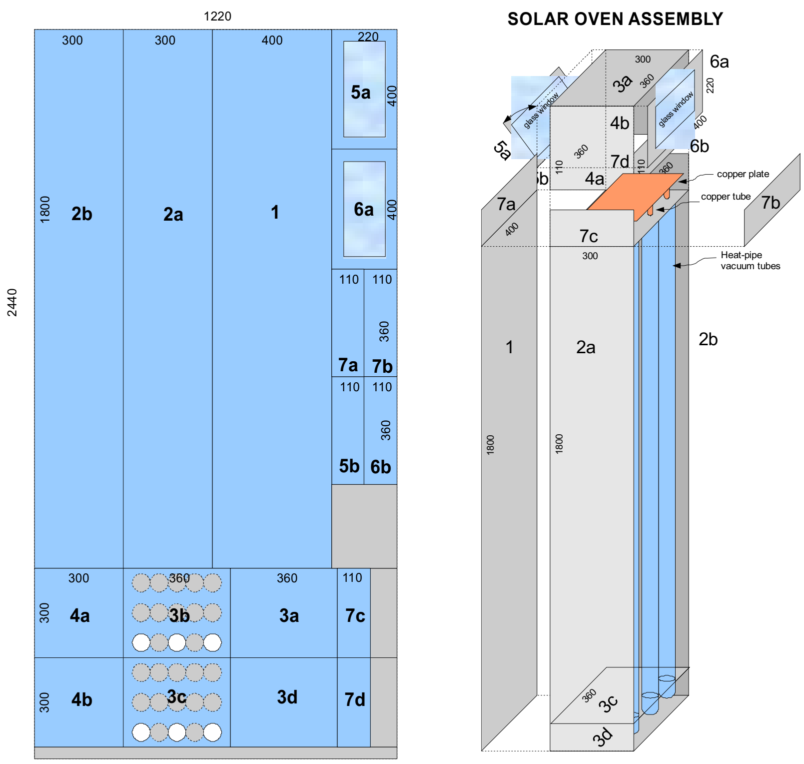

Fig. 9: Cutting diagram and assembly plans

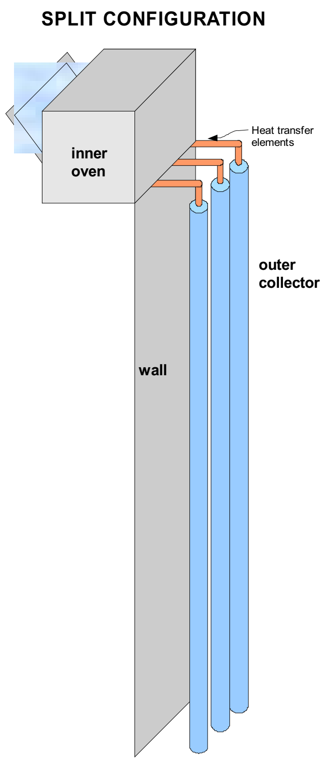

Fig. 10: Proposal of split configuration

5.4. Proposed modifications

The front and back of the oven cavity can be made of glass or plastic (heat resistant, like polyester film).

The inside of the oven can also be coated with metal sheet, glass or polyester to improve the thermal characteristics.

Heat-pipes in the vacuum tubes tend to elevate due to expansion of hot air, what can displace or break the heat transfer structure. It has been found a solution that consists of remove the silicone seal or make a slot to allow exit of air to the cavity of the oven. Fig. 11 shows elevation of the tubes (left) and the solution (right).

Fig. 11: Raising of the evaporators due to hot air pressure and solution

6. Architectonic integration

The use of vacuum tubes avoids the problem of reorientation, allowing to place the solar collector fixed on a facade or wall. Such collectors work well in a vertical position, which improves the performance in winter or for low sun elevations.

This system allows a split configuration (Fig. 10) which is formed by an external unit with vacuum tubes and an internal unit with the oven cavity, connected by a high thermal conductivity material with sufficient insulation.

The oven is designed to be opened by the rear side, so it can be accessed from inside the house through a hole in the wall or through a window (Fig. 12).

The front can have a window that serves two functions: to increase the collecting area of the oven and also to light the oven. This surface can be increased or make the oven completely transparent.

The back also has a window used to view the status of cooking as in conventional ovens.

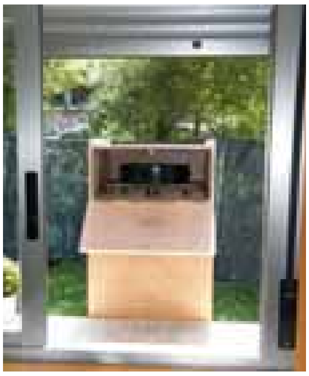

Fig. 12: Example of access to the oven from inside the house

7. First tests and suggestions for improvement

The prototype of solar oven presented in this article should be viewed only as a viability study and cannot be expected a good performance. The first tests have shown that can reach temperatures as high as 80°C without good insulation. Among others, the following changes are planned:

- five tubes placed in the front row instead of three
- incorporate a rear reflector to increase the radiation in the tubes
- improve the seal at the entrance of the tubes to the cavity
- experiment with different thicknesses and types of insulation in the cavity
- try different types of thermal diffusers (copper plate welded to the tubes)
- test reflective materials covering the inside of the oven
- incorporate glass or plastic windows to increase solar radiation and light the oven
- try different types of cavities completely made of glass or plastic
- remove the heat pipes and use the hot air generated as transmission fluid.

8. Acknowledgements

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