THERMAL SOLAR EXPERIMENTAL MODEL EQUIPPED WITH FRESNEL LENSES

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REZUMAT. În această lucrare sunt prezentate rezultate experimentale obţinute prin testarea unor lentile Fresnel în vederea unor aplicaţii termice ale energiei solare. Experimentele au arătat că temperatura unei plăci de aluminiu plasată în focarul unei lentile Fresnel din masă plastică, cu aria de 0.52 m² atinge aprox. 560°C. A fost construit un model experimental echipat cu două lentile Fresnel din masă plastică, cu aria de aprox. 0,13 m² fiecare, una fiind cu focar punctiform, iar cealaltă cu focar liniar. Modelul a fost de asemenea echipat cu două calorimetre, masa apei din fiecare calorimetru fiind de 2 kg. Determinările experimentale au fost efectuate în luna noiembrie – 2014, pe terasa unei clădiri cu 7 niveluri, în condiţii de vânt. Temperatura afost măsurată cu termometre PT100. Intensitatea radiaţiei solare a fost măsurată cu pyranometrul Kipp-Zonen. A fost determinată o eficienţă medie a instalaţiei cu lentilă cu focarul linear de 13,98 % şi o eficienţă medie a instalaţiei cu lentilă cu focarul punctiform de 16.48 %. Starea de saturaţie a curbei de evoluţie a temperaturii apei din calorimetru a fost atinsă mai repede la instalaţia cu lentila cu focarul linear decât la instalaţia cu lentila cu focarul punctiform. Studiul recomandă ca în instalaţiile termosolare cu lentile Fresnel pentru încălzirea apei menajere să se folosească lentilele cu focarul punctiform.

Cuvinte cheie: Fresnel, focar linear, punctiform, transmitanţă, apertură, interceptare, striaţii, eficienţă.

ABSTRACT. In this paper, experimental results obtained with Fresnel lenses tested for solar thermal applications are reported. Experiments have shown that the temperature of an Aluminum plate placed at the focal point of a 0.52 m² plastic Fresnel lens has reached approximately 517 °C. An experimental thermal solar model has been built containing a linear and a point focus plastic Fresnel lenses with an area of about 0.13 m² each and two calorimeters filled with 2 kg of water each. Experiments have been performed in November 2014 on the terrace of a 7 stores building, in windy conditions. Temperature of the working agent has been measured with PT100 thermometers and irradiance has been measured with a Kipp-Zonen pyranometer. A 13.98% average efficiency of the installation equipped with linear focus lens and a 16.48% average efficiency of the installation equipped with point focus Fresnel lens have been determined. The saturation state of the temperature evolution curve has been reached faster in the case of the installation equipped with linear focus lens than in the case of the installation equipped with point focus lens. The study recommends that the thermal solar plants with Fresnel lenses for domestic heating water to use lenses to a point focus.

Key words: Fresnel lens, point focus, linear focus, transmittance, aperture, interception, facet, efficiency.

1. INTRODUCTION

Energy incident on solar installations has to be collected from a large solid angle and has to be concentrated on a surface that is much smaller than the collecting one. The end receiver must be illuminated as uniformly as possible. Fresnel lenses can be used for collecting solar energy, since rendering of the image of the source is not important in this application [18]. Research concerning collecting solar energy by means of Fresnel lenses for solar energy applications has been started in the period 1975-1980 [12,13].

Fresnel lenses used in present day applications are fabricated from a plastic material and are composed of a plane-parallel plate having a thickness of 1.5–5 mm. Facets (also referred to as ridges or *grooves*) are impressed on the plate. A large variety of types and dimensions are available, having focal distances in the range 5–700 mm.

Facets can form a circular or a linear pattern. An imaging concentrator is obtained in the first case and a non-imaging one in the second case. Lenses are of rectangular shape, having a width of 15–700 mm and a length up to 1000 mm. Linear focus lenses may be curved when incident radiation has to be concentrated on cylinders.

Plastics currently used for fabricating Fresnel lenses for solar energy applications are acryl, rigid vinyl and polycarbonate. These materials have a transmittance greater than 80% for wavelengths in the range 400-1500 nm. The acryl (polymethyl methacrylate – PMMA) has an index of refraction of 1.49, a mass density of 1.19 g/cm^3, can bear temperatures up to 80°C and its properties are not modified by direct solar irradiation.

Linear focus Fresnel lenses can be mounted on fixed systems (i.e. without tracking) if working in conjunction with a second concentrator and a solar diffuser. Concentration factors of 10–20× can be obtained. Lenses with two-dimensional focus achieve a concentration factor of 100×. If a second concentrator (a spherical lens) is added, the concentration factor can reach 500×. Acceptance angles are of the order of a few degrees [7].

When exposed to solar radiation, Fresnel lenses separate the direct radiation from the diffused one, opening the way for lighting applications inside buildings [6].

In the years around 2000, it was considered that Fresnel lenses represent the best option for the conception of medium and large PV systems from a financial point of view [17]. Fresnel lenses are recommended for PV panels because the radiation is distributed uniformly on the solar cells [11]. In [21], it is shown that requirements for the tracking system are minimal when using non-imaging Fresnel concentrators.

Systems with medium concentration ($10\times<C<100\times$) are realized either with Sun tracking lenses, or with a fixed lens and a mobile radiation receiver. Low concentration systems ($C<10\times$) are built using other solutions that do not rely on Fresnel lenses [4]. In a proposed solution, Fresnel lenses transmit a proportion of 60-80% of the direct radiation to thermal or PV collectors installed on buildings and the difference is used for indoor lighting [19].

One problem raised by Fresnel lens-based concentrators consists of the drop in conversion efficiency of PV cells caused by heating, which increases proportionally with the incident solar radiation intensity. In the worst case, a 50% decrease of efficiency of PV cells with respect to standard test conditions has been reported, at an irradiance of 1000 W/m^2 and an ambient temperature of 50^{o}C (but without forced convection) [20]. A solution for this problem has been proposed, consisting of combined thermal-PV modules that keep a low temperature for the PV cells and consequently have a larger efficiency [4, 5].

Innovative structures for Fresnel lenses and solar radiation collecting systems in view of obtaining improved performances have been proposed in the last years. Fresnel lenses which are dome-shaped, non-imaging [1], or which have an increased concentration factor without relying on secondary optics elements have been built [15]. Other solutions include elliptical lenses for correcting for chromatic aberration [22] and modular lenses [16].

Natural conditions may degrade operation and performances of the Fresnel lenses. Dust particles with diameters of 11–22.5 μm contaminate the surface of the lens and form aggregates having diameters of approximately 40 μm. The chemical and optical degrading cause a drop of transmittance by 10% and the useful surface can be reduced by 3.98%. Periodic dry cleaning of the surface of the lens by using an electric field is recommended [3]. Another report shows that dust particle deposition, with particles diameter of 6.44 μm and a surface density $N = 2\cdot10^6\,\text{cm}^{-2}$ causes a drop in transmittance of 31% for radiation of wavelength λ = 0.8 μm, at normal incidence [2]. In a study concerning the impact of wind containing sand particles, it has been observed that the transmittance of the lenses decreased when the impulse of incident particles increased. In the same conditions, the durability of glass lenses has been double with respect to the PMMA based lenses [14].

Several advanced procedures for assessing performances of Fresnel lenses have been devised in the last years. For example, optical efficiency, spectral transmittance and concentration factor can be measured by means of a Lambertian diffuser placed at the focal locus, a CCD camera and optical power and spectrum measuring devices [6]. The procedure can be applied to both linear and point focus lenses.

In this paper, we consider application of Fresnel lenses to installations for heating water in view of domestic use. Previous studies indicated that the climate in the region of Timisoara, Romania is appropriate for this kind of applications [9]. In the next section, we present results of tests performed on Fresnel lenses, both with point and linear focus, we have used. The conception and construction of a measuring experimental setup are presented in Section 3 and results of measurements and tests are reported in Section 4. Conclusions are drawn in the last section.

2. EXPERIMENTAL ASSESSMENT OF FOCUSING OF SOLAR RADIATION BY FRESNEL LENSES

The experimental setup, represented in Fig.1, has been conceived and realized within the laboratories of the Department of Physical Foundations of Engineering (BFI), the Department of Measurements and Optical Electronics (MEO) and the Department of Mechatronics from the Politehnica University of Timisoara, Romania. Experiments have taken place in June, 2014.

The elements in Fig.1 are as follows: A1A2 – support; A1A3 – plate inclined at an angle *s* with respect to the horizontal plane, where *s* is the declination at the place of the measurements; C1C2 – support; B1B2 – rod for rotating the support C1C2;

C2C3 – Fresnel lens; D1D2 – aluminum or wooden plate that can be displaced along the line A2A3; (F) – focus; *f* – focal distance; (S) – solar rays; A2A3 – rack graded in (cm). Balance weights are mounted at points A1 and C1 for providing mechanical equilibrium and stability of the spatial setup.

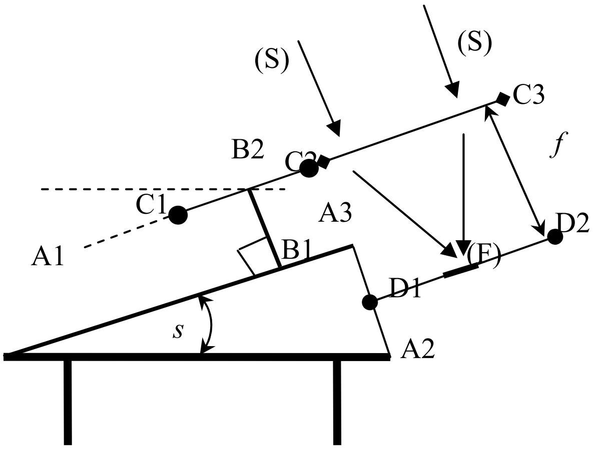

Fig. 1. Conception diagram of the equatorial.

At noon, the azimuthal angle of the lens is zero. Normal incidence of rays on the lens can be realized, at any moment, by rotating the support C1C2 around the axis B1B2 eastwards or westwards, with an angle equal to the hourly angle of the Sun. The plate D1D2 can be displaced upwards or downwards until the illumination at point F reaches the maximum. Then, the focal distance *f* can be measured directly.

As an example, we consider measurements performed on a PMMA lens, mounted on a wooden frame, having a circular contour of the successive Fresnel zones and having an input aperture $A_1 = 0.52$ m^2, an interception factor $\gamma = 0.80$, a mass $m = 2.5$ kg, a measured focal distance $f = 74$ cm and a measured radius of the focal spot $r = 4$ cm, corresponding to a surface of the focal spot $A_2 = 16\pi \times 10^{-4}$ m^2.

A photograph of the stand is presented in Fig. 2 (a), on which the lens, the frame of the lens, the burnt wooden plate and the metal plate are visible. A detail of the focal spot is presented in Fig. 2 (b).

(a) (b)

Fig. 2. Photograph of the experimental setup: (a) Fresnel lens and support plates for the focal spot; (b) the focal spot on the aluminum plate.

We denote by I_1 the solar irradiance at normal incidence, which has been measured with a Kipp-Zonen pyranometer and by I_2 the average irradiance at the focus, which can be calculated by means of equation (1):

$$I_2 = \frac{\gamma \tau A_1 I_1}{A_2} \tag{1}$$

For a measured incident normal irradiation $I_1 = 748$ W/m^2, the interception factor γ and surfaces A_1 and A_2 given above and a transmittance $\tau = 0.92$ for a 2 mm thick PMMA plate (absorption is negligible in thin plates of PMMA) [10], we obtain $I_2 = 5.70 \times 10^4$ W/m^2.

By considering that thermal losses by radiation from the focal spot are equal to convection losses, by neglecting conduction losses and by taking into account that the aluminum plate, exchanges energy through one face (the other face being insulated with a wooden plate), we have

$$\alpha I_2 = 2\varepsilon\sigma T^4 \tag{2}$$

where $\alpha = 0.10$ is the absorption factor for incident energy [8], $\varepsilon = 0.2$ is the emissivity of an oxidized aluminum commercial sheet at high temperature [23], $\sigma = 5.67 \times 10^{-8}$ Wm^{-2}K^{-4} is the Stefan-Boltzmann constant and T (K) is the temperature. This gives a temperature of 708 K or 517°C. Since the melting point for aluminum is at 660°C, this result explains the incandescence of the focal spot on the aluminum plate in Fig. 2 (b) without melting.

3. EXPERIMENTAL THERMAL SOLAR MODEL WITH FRESNEL LENSES

An experimental setup for a comparative assessment of point and linear focus Fresnel lenses used for domestic water heating applications has been devised and realized in cooperation by Departments of BFI and MEO and the Energosophia enterprise. The conception diagram of the installation is represented in Fig. 3.

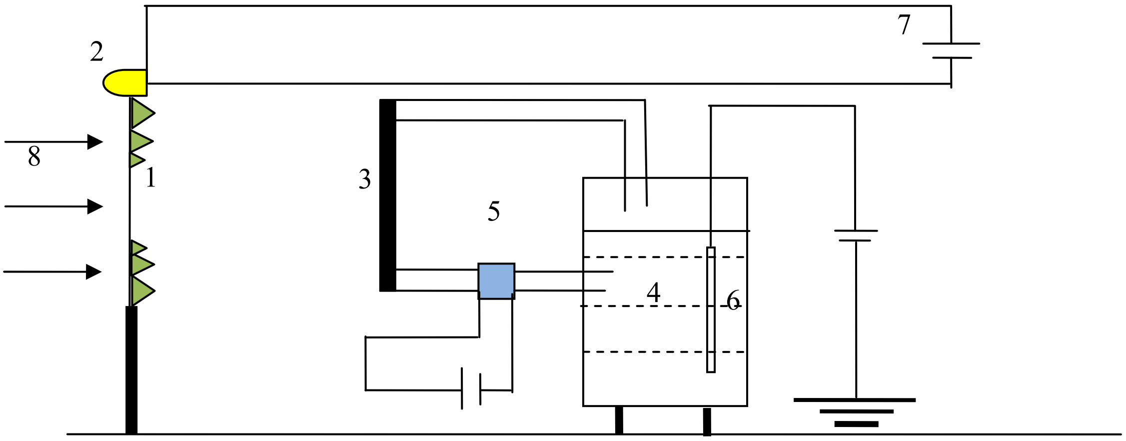

Fig. 3. Conception diagram of experimental setup with Fresnel lenses.

(a) (b)

Fig. 4. Photograph of the thermal experimental setup: (a) position of the lenses; (b) calorimeters and measuring devices.

The elements in Fig. 3 are as follows: *1* – Fresnel lens; *2* – Kipp-Zonen pyranometer; *3* – pipe placed at the focus; 4 – calorimeter with water; 5 – water pump; *6* – electronic thermometer with Pt100; *7* – rectifier; *8* – incident solar rays. The two lenses, one with point focus and one with linear focus have been placed on the front wall of a box with dimensions 77/53/45 cm. The black copper pipe at the focus of the point focus lens has had a length of 5 cm and an outer diameter of 22 cm. The black copper pipe at the focus of the linear focus lens has had a length of 33.5 cm and an outer diameter of 22 mm. The wall of the pipes had a thickness of 2 mm. Calorimeters have been insulated with polystyrene foam and both contained 2 kg of water. The power of the pump has been 2 W.

The Fresnel lens with linear focus has the following characteristics: material PMMA; dimensions 40 cm × 32 cm; surface A_l = 1280 cm^2 focal distance f_l = 62,5 cm; mass m_l = 582 g, transmittance $\tau = 0.92$; interception factor γ = 0.80; the focal spot is a rectangle with dimensions 32 cm and 0.5 cm; surface of the focal spot $A_{f,l}$ = 16 cm^2. The facets are linear, parallel to the smaller side.

The Fresnel lens with point focus has the following characteristics: dimensions 35 cm × 35 cm; surface A_p = 1225 cm^{2,}; the focal spot is circular, with a diameter d_p = 0.4 cm; surface of the focal spot $A_{f,p}$ = = 0.502 cm^2; focal distance f_p = 37.3 cm, mass m_p = = 557 g; transmittance $\tau = 0.92$; interception factor γ = 0.80, surface of the focal spot $A_{f,l}$ = 16 cm^2. The facets are circles in succession. The optical center coincides with the geometric one.

A photograph of the installation is presented in Fig. 4.

4. EXPERIMENTAL RESULTS

Measurements have been performed on November 4, 2014 on the terrace above the seventh floor of the building where the headquarters of the MEO Department is located, in windy conditions. Results of direct measurements are reported in Table 1 as follows: global radiation G (W/m^2); diffuse radiation D (W/m^2); direct radiation I (W/m^2); ambient temperature T_a (^{o}C); temperature of water in calorimeters: T_l (^{o}C) for the linear focus case and T_p (^{o}C) for the point focus case.

Table 1. **Irradiance (W/m^2) and temperatures (°C)**

Hour	G (W/m^2)	D (W/m^2)	I (W/m^2)	T_l (°C)	T_p (°C)	T_a (°C)
12:09	962.5	192.5	770.0	21.4	22.3	11.0
12:13	975.6	195.0	780.6	21.9	23.1	11.5
12:16	975.0	195.2	779.8	22.6	23.6	11.5
12:21	975.0	195.1	779.9	23.1	24.4	12.0
12:26	950.3	190.0	760.3	23.6	2.9	13.0
12:31	950.0	190.3	759.7	24.1	25.6	15.0
12:35	962.5	192.5	770.0	24.6	26.1	16.0
12:40	962.5	192.5	770.0	25.1	26.7	16.0
12:44	973.8	194.8	779.0	25.6	27.2	16.5
12:50	962.5	192.5	770.0	26.1	27.8	16.5
12:55	962.5	192.5	770.0	26.7	28.3	17.0
13:01	967.5	193.5	774.0	27.2	28.9	17.0
13:05	981.3	196.3	785.0	27.8	29.5	17.0
13:13	970.0	194.0	776.0	28.3	30.2	17.0
13:21	960.0	192.0	768.0	28.8	30.7	17.0
13:37	936.3	187.3	749.0	29.2	31.5	17.5
13:42	940.0	188.0	752.0	29.5	31.7	17.5
13:47	948.8	189.8	759.0	29.6	32.0	18.0
13:52	943.8	188.8	755.0	29.9	32.2	19.0
13:57	932.5	186.5	746.0	29.9	32.4	19.0

The following calculated quantities are reported in Table 2: time interval between consecutive measurements form Table 1 $\Delta\tau_i$ (min); solar energy incident on each cell $W_i = I_{im} A_{lens} \Delta\tau_i$ (J), where I_{im} is the arithmetic mean of efficiencies at the ends of the interval; raise of temperature in each calorimeter in the time interval $\Delta T_i = T_{i+1} - T_i$ (°C); quantity of heat accumulated in the calorimeters in the time interval $Q_i = mc\Delta T_i$, with c = 4185 Jkg^{-1}(°C)$^{-1}$ (specific heat of water); average efficiency of the lens $\eta_i = Q_i / W_i$.

Table 2. **Efficiency of installations equipped with point and linear focus Fresnel lenses**

Time Interval (min)	$I_{i,m}$ (W/m^2)	$W_{i,l}$ (J) linear focus	$W_{i,p}$ (J) point f.	$\Delta T_{i,l}$ (°C) linear f.	$\Delta T_{i,p}$ (°C) point f.	$Q_{i,l}$ (J) lin. f.	$Q_{i,p}$ (J) point f.	$\eta_{i,l}$ (%) lin. f.	$\eta_{i,p}$ (%) point f.
4	775	23808.0	22785.2	0.5	0.8	4185	6696	17.58	29.39
3	780	17971.2	17199.0	0.7	0.5	5859	4185	32.60	24.33
5	780	29952.0	28665.0	0.5	0.8	4185	6696	13.97	23.36
5	770	29568.0	28297.5	0.5	0.5	4185	4185	14.15	14.79
5	760	29376.0	27930.0	0.5	0.7	4185	5859	14.25	20.98
4	765	23654.4	22491.2	0.5	0.5	4185	4185	17.69	18.61
5	770	29737.0	28297.5	0.5	0.6	4185	5022	14.07	17.75
4	774,4	23789.6	22767.2	0.5	0.5	4185	4185	17.59	18.38
6	774,4	35481.6	34150.8	0.6	0.6	5022	5022	14.15	14.71
5	770	29644.5	28297.5	0.5	0.5	4185	4185	14.12	14.79
6	772	35919.6	34045.2	0.6	0.6	5022	5022	13.98	14.75
4	779,5	23976.8	22917.2	0.5	0.6	5022	5022	20.94	21.91
8	780,5	47431.2	45893.6	0.5	0.7	4185	5859	8.20	12.77
16	758,5	93204.8	89198.4	0.4	0.5	3348	4185	3.59	4.69
5	750,5	28819.0	27581.0	0.3	0.8	2511	6696	8.71	24.28
5	755,5	29011.0	27764.0	0.1	0.2	837	1674	2.89	6.03
5	757	29069.0	27819.5	0.3	0.3	2511	2511	8.64	9.03
5	750,5	28819.0	27581.0	0.00	0.2	0,00	1674	0.00	6.07
$\eta_{m,l}$ (%) linear focus (average)	13.98								
$\eta_{m,p}$ (%) point focus (average)	16.48								

5. CONCLUSIONS

An experimental setup has been devised and realized for assessing the efficiency of thermal solar installations equipped with Fresnel lenses in view of water heating for domestic use. Experiments have been performed in natural, realistic conditions. Both lenses with linear and point focus have been tested.

Direct measurements allowed calculating an average efficiency of the installation equipped with linear focus Fresnel lens of 13.98% and an average efficiency of the installation equipped with point focus Fresnel lens of 16.48%. Saturation has been reached faster by the installation with linear focus lens than by the installation with point focus lens.

Installations equipped with point focus lenses seem to be more appropriate for applications of heating water for domestic use that installations equipped with linear focus Fresnel lenses.

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