The fresnel lens concept for solar control of buildings

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ABSTRACT

The fresnel lens concept is suggested for solar control of the building in order to keep the illumination and the interior temperature at the comfort level. The collection of 60%-80% of the transmitted solar radiation through the fresnel lens on linear absorbers leaves the rest amount to be distributed in the interior space for the illumination and thermal building needs. The fresnel lenses can be combined with Thermal, Photovoltaic, or hybrid type Photovoltaic/Thermal small width absorbers to extract the concentrated solar radiation in the form of heat, electricity or both. Laboratory scale experimental results are presented in the paper, giving an idea about the application of this new optical system for lighting and cooling control of buildings.

1. INTRODUCTION

The daylight that penetrates the transparent apertures of a building affects illumination and temperature of the interior spaces. Apart of typical windows, the sunspace, the atrium, the gallery or other light-guide designs are used in architecture to provide more solar radiation into the building. These constructions are used to replace artificial illumination and thus to save electricity, but daylight plays a more important role considering visual comfort, communication and other aspects. In addition, the distribution of daylight on external and internal building surfaces, results in most cases to non-uniform energy flow and therefore solar control is often necessary. An extensive presentation of methods and tools developed on natural ventilation process is included in the Design Handbook of M. Santamouris (1998). Detailed analysis of alternative methods for effective cooling of buildings are referred by Santamouris et al (1995) and Jacovides et al. (1995) regarding earth-to-air heat exchangers. Building cooling loads can be reduced by applying green roofs (Mihalakakou et al., 2001), by radiative cooling (Mihalakakou et al., 1998, Errel and Etzion, 2000) and by improving air velocity in single sized natural ventilation configuration (Daskalaki et al., 1996).

Several modes of shading are used in order to reduce the absorbed solar energy by the building and to keep the average temperature at the comfort level. The visible spectrum of solar radiation affects illumination, while the infrared part causes mainly the heating effect when absorbed by the building elements. In medium and high latitude countries the amount of solar energy is not usually enough and artificial light and heat supply is needed in most months of the year. On the contrary, in low latitude countries the incoming solar radiation is more than the necessary for visual and thermal comfort most months and its reduction is a common practice.

Shading devices are studied on a PASSYS test cell (Tsangrassoulis et al., 1996) and daylight transmittance through double-glazed windows with motorised reflective blinds was determined (Athienitis and Tzempelikos, 2002). Field measurements on daylighting control have been considered for energy saving (Li and Lam, 2001) and investigations for heat transfer across a PV wall were determined regarding the cooling load component (Yang et al., 2000). In addition, flat or curved (CPC) reflectors have been suggested to be used as lightguides and to provide sunlight the spaces of the building interior (Molteni et al, 2002, Scartezzini and Couvvet, 2002).

In this paper we study the application of new transparent materials, the glass type linear fresnel lenses, aiming to achieve illumination and temperature control of buildings and in addition energy gain by the surplus incoming solar radiation that is extracted from the interior space. Fresnel lenses are optical devices for solar radiation concentration, which are used in several solar energy systems as the thermal collectors and photovoltaics because of their attractive features. Their advantages are the low volume and weight, the smaller focal length and the low cost, compared to the thick ordinary lenses. Among the works on the fresnel lenses we can refer the study on the fresnel lens curved surface that aims to minimize lens focal length (Kritchman et al, 1978) and the truncated stationary fresnel lenses (Leutz et al, 1999). The use of fresnel lenses as a transparent covering material for lighting and energy control of internal spaces has been introduced by Jirka et al, 1998.

The fresnel lenses are suggested to be combined with Thermal, Photovoltaic, or hybrid Photovoltaic/Thermal small width absorbers to extract the concentrated solar radiation in the form of heat, electricity or both, for simultaneous or later use (Tripanagnostopoulos et al, 2004). The extracted energy can be stored as heat (e.g. hot water storage or underground storage) to be used during night or as electricity (batteries or electricity grid) to cover electrical needs. The fresnel lens concept is suggested for solar control of the building in order to keep the illumination and the interior temperature at the comfort level. Laboratory scale experimental results are presented in the paper, giving an idea about the application of this new optical system for lighting and cooling control of buildings.

2. FRESNEL LENS CONCEPT

Several types of fresnel lenses have been investigated, consisting of linear or circular grooves. Fresnel lenses of 2D type (linear geometry lenses) are more practical than 3D type (circular geometry lenses), and as they have East-West lens axis orientation they need less movements for system orientation to the sun. Both sides of a fresnel lens could be grooved, but in practice they are grooved on the surface facing down, having smooth their flat surface towards the sun, to reduce transmission losses and accumulation of dust and dirt.

The advantage of linear fresnel lenses to separate the direct from the diffuse solar radiation makes them suitable for illumination control in the building interior space, providing light of suitable intensity level and without sharp contrasts. The direct part of the incident solar radiation can be concentrated on an absorber strip, located at the focal position of the applied optical system and can be taken away to achieve lower illumination level and also to avoid the overheating of the space.

The linear fresnel lens can be combined with linear multifunction absorbers that convert the concentrated solar radiation into heat, electricity or both. This compound systems can adapt illumination control during day, storing the surplus energy for space heating during night, to contribute in the ventilation needs during day and to apply illumination by artificial light during night or to cover other building electrical loads. In low intensity solar radiation, due to the position of sun relative to the building roof (low sun altitude) or because of the clouds, the absorbers can be out of focus leaving the light to come in the interior space and to keep the illumination at an acceptable level.

In this paper we give the distribution of the concentrated solar radiation on the focal plane of a linear fresnel lens and the effect of the absorber size and the incidence angle on the collected radiation and interior space temperature. The study includes design concepts for linear absorbers of thermal (T), photovoltaic (PV) absorbers and is emphasised to hybrid photovoltaic/thermal (PVT) type, which can be of air or water heat extraction. These new solar energy systems convert solar radiation simultaneously into electricity and heat. Recent works on PVT systems include modelling results on liquid type systems (Bergene and Lovvik, 1995) test results for an integrated PV/T system with hot water storage (Huang et al, 2001) and theoretical and experimental results from several investigated prototypes (Zondag et al 2002, 2003).

An extensive study regarding performance improvement of hybrid PVT systems has been done in Physics Department at University of Patras (Tripanagnostopoulos et al 2001, 2002, 2003), where new designs and results on PVT systems are presented. The hybrid PVT systems can be combined with linear fresnel lenses and can be used for space heating and cooling of the inside space of buildings. The combination of fresnel lenses with hybrid PVT absorbers is a new concept and aims to maximise the energy conversion output of fresnel lens type solar energy systems that are used as transparent material.

Considering the energy conversion into heat, the concentrated solar radiation is absorbed and increases the temperature of a pipe or of a fin-type absorber. The heat is transferred to the circulating fluid, which is usually the water and the hydraulic system can be connected with a storage for later use. When applying this system we consider the water heating during the time periods of the day, mainly during noon, that there is a surplus of solar radiation. The stored hot water can circulate through space heaters during night to contribute in the heating needs of the building and to keep air temperature at an acceptable level. In the case of using photovoltaics as absorbers, the produced electricity can be used directly for the electrical needs, it can be transferred to the electricity grid or it can be stored in batteries to be used in other time period.

PV modules convert a small part of the incoming solar radiation to electricity, with the greater part being converted into heat. This effect increases their temperature, resulting to its efficiency drop. PV and Thermal sub-systems can be combined in one unit, consisting the hybrid PVT system, which provides simultaneously electricity and heat and can keep PV electrical efficiency at a satisfactory level. The extracted heat from the PV module results to temperature rise of the heat removal fluid and aiming to use it later, it can be stored in a storage tank. In PVT system applications and considering that the electricity is of priority, the operation of the PV modules at lower temperatures is necessary in order to keep PV cell electrical efficiency at a sufficiently higher level. This demand limits the operation range of PVT system thermal unit in lower temperatures and the extracted heat can be mainly used for low temperature thermal needs. Regarding the integration of fresnel lens/PVT systems on the transparent roof of buildings it is necessary to consider the useful electrical and thermal output together with the benefits in illumination control and ventilation gain in order to achieve cost effective installation.

In Figure 1 we present the design principle of the fresnel lens (left), which is a non-imaging concentrator and therefore the refractive rays form a diffused image of sun at the focal length. In the same figure (right), we present six types of possible solar radiation absorbers, where in the first line are the fin with pipe type for water heating, the air duct for air heating and the photovoltaic type absorber. In the second line there are the hybrid PVT type absorbers for water heating, for air heating and also for water heating with additional glazing and thermal insulation.

3. EXPERIMENTAL STUDY

In Figure 2 we give the distribution of the concentrated (C) solar radiation on the focal plane of the used linear fresnel lens for zero incident angle ($z=0^o$) and azimuth fresnel lens plane angle ($\gamma=0^o$) and for focal length f=42 cm (a). We also present the distribution of the concentrated solar radiation for $z=0^o$ and $\gamma=45^o$ (b), for $z=23^o$ and $\gamma=0^o$ (c), and also for $z=23^o$ and $\gamma=45^o$ (d).

We calculated the percentage of the collected solar radiation by applying absorbers of 10 cm and 5 cm in width. The presented results (Fig. 3) are obtained for the absorbers in two positions: on the focus (F) and also out of focus (NF), are based on incident – diagram (a) -and transmitted – diagram (b) – solar radiation and correspond

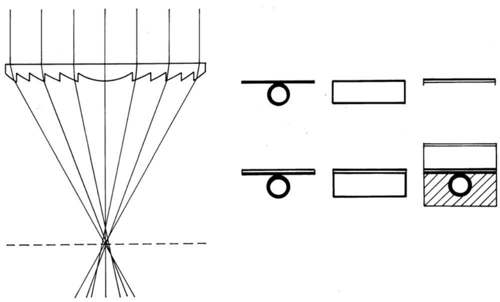

Figure 1: The geometry of the linear Fresnel lens, with indication of the concentrating solar radiation (left) and alternative absorbers of Thermal (T), PV and PVT type (right).

to the above four cases (1,2,3,4) of the presented distribution of concentrated solar radiation (a), (b), (c) and (d).

The diagrams of Figure 3 show that most of

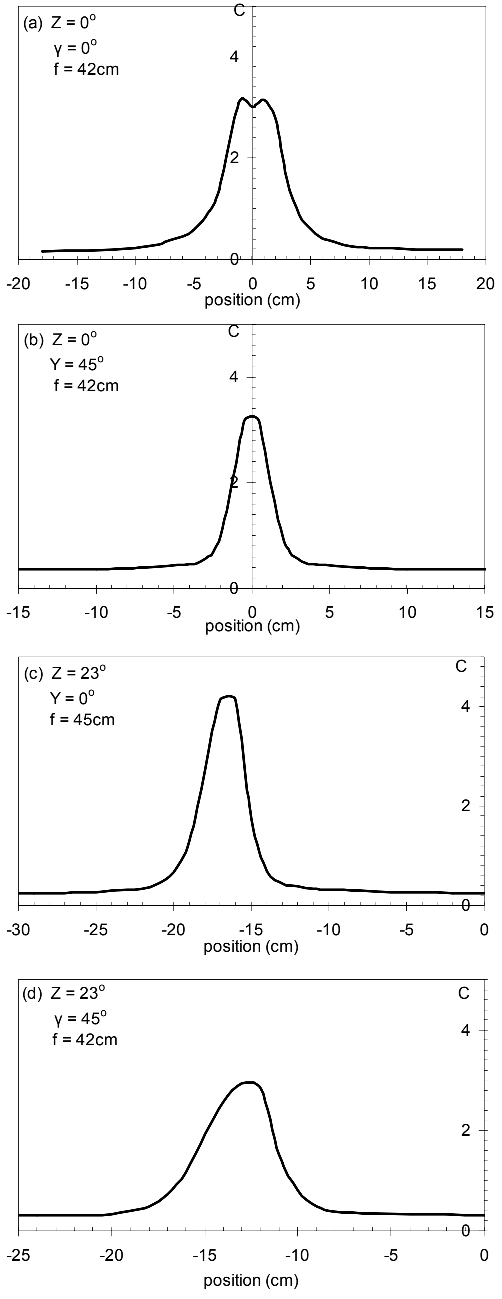

Figure 2: Diagrams showing the distribution of concentrated solar radiation by the used fresnel lens.

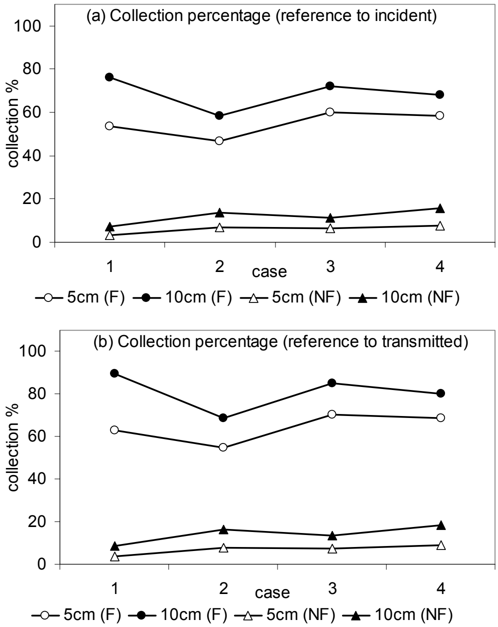

Figure 3: Collected solar radiation for the cases of Fig. 2 and absorbers (5cm, 10cm) in focus (F) or no focus (NF).

the transmitted solar radiation from the glazed roof can be absorbed by the receiver, controlling the illumination of the interior space and also providing heat and electricity to cover several energy needs of it. The collection of 60%-80% of the transmitted solar radiation through the transparent cover on linear simple (T, PV) or multifunction (PVT) absorbers, leaves the rest amount of solar radiation to be distributed in the building space for the illumination needs.

We performed experiments under clear sky conditions with a simulative device, where we could measure the effect of the absorption of the 60% of the transmitted solar radiation to the interior space illumination and temperature. Regarding the reduction of illuminance of the interior space, we present in Figure 4a the incoming and the transmitted solar radiation during day, for south orientation of the fresnel lens. We indicate the results for the absorbing (USED) and not absorbing (NOT USED) transmitted solar radiation in the time interval of 10:30 to 14:30 hour. The effect of solar radiation extraction is shown in Fig. 4b for the system without natural ventilation (no-NV) and in Figure 4c for natural ventilation (NV).

We also present the effect on the interior temperature reduction of absorber operation in low temperature (inserting water 20^{o}C) and in medium temperature (inserting water 50^{o}C) from 10:30 to 14:30, in comparison with the obtained temperature without the cooling effect from the absorber operation (T). The results show that for the 20^{o}C cooling mode, we observe that the temperature reduction exceeds the 10^{o}C for the no-NV or the 6^{o}C for NV mode. For the effective absorber operation at 50^{o}C, (the system operates as a thermal collector), the interior temperature reduction is about 5^{o}C (no-NV) and 3^{o}C (NV). The application of a PV or a PVT absorber results to electrical or both electrical and thermal output, which can contribute to cover building energy needs. We estimate that the cooling effect by the suggested system can adapt about 50% of the needs, only from the heat extraction by the absorber operation, which can be higher if we consider fan or AC operation by the provided electricity from the photovoltaics.

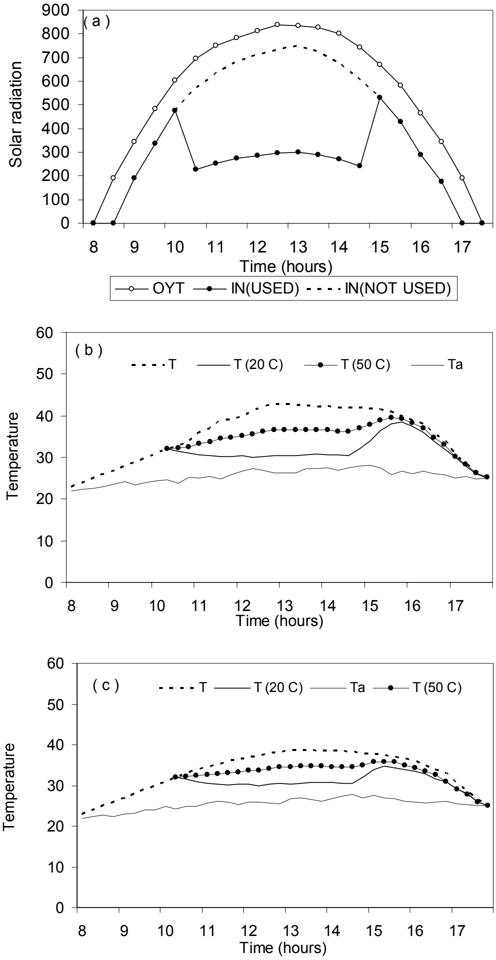

Figure 4: Solar radiation and temperature results for system operation at 20^{o}C and 50^{o}C from 10:30 to 14:30.

4. CONCLUSION

A new concept for the illumination and temperature control of buildings based on the use of linear glass type fresnel lenses as transparent covering material is presented. The lenses separate the direct from the diffuse solar radiation and can be combined with multifunctional solar radiation absorbers of thermal (T), photovoltaic (PV) or hybrid photovoltaic/thermal (PVT) type. This new devices can be used in alternative modes, aiming to effective lighting and temperature control of buildings and also for other energy requirements according to the local weather conditions and the building needs. Our study includes diagrams with the solar radiation distribution on the focal plane of the used fresnel lens as function of the incident angles of the incoming solar radiation on lens plane. In addition, we include results regarding the collected radiation by absorbers of 5 cm and 10 cm in width, showing that 60%-80% of the transmitted of radiation can be absorbed and used directly or through thermal and electrical storage to cover energy needs of buildings. Using a simulative lens/absorber experimental device, we observed that the temperature of the interior space can be reduced by about 3^{o}C to 10^{o}C, depending on the use of openings to enhance the natural ventilation of air. The obtained results show that the system is promising for lighting and temperature control of the interior spaces of buildings, providing simultaneously heat and electricity and contributing therefore to the energy needs of them.

REFERENCES

Athienitis A.K. and A. Tzempelikos, 2002. A methodology for simulation of daylight room illuminance distribution and light dimming for a room with a controlled shading device. Solar Energy 72:271-281.

Bergene, T. and O.M. Lovvik, 1995. Model calculations on a flat-plate solar heat collector with integrated solar cells. Solar Energy 55: 453-462.

Danny, H.W.L. and J.C. Lam, 2001. Evaluation of lighting performance in office buildings with daylighting controls. Energy and Buildings 33:793-803.

Daskalaki, E., M. Santamouris, A. Argiriou, C. Helmis, D.N. Asimakopoulos, K. Papadopoulos and A. Soilemes, 1996. On the combination of air velocity and flow measurements in single sided natural ventilation configurations. Energy and Buildings 24:155-165.

Erell, E. and Y. Etzion, 2000. Radiative cooling of buildings with flat-plate solar reflectors. Building and Environment 35:297-305.

Hongxing, Y., J. Burnett and J. Jie, 2000. Simple approach to cooling load component calculation through PV walls. Energy and Buildings 31:285-290.

Jacovides C.P., G. Mihalakakou, M. Santamouris and J.O. Lewis, 1996. On the ground temperature profile for passive cooling applications in buildings. Solar Energy 57:167-175.

Jirka, V., V. Kuceravy, M. Maly, J. Pokorny and E. Rehor, 1998. The architectural use of glass raster lenses. In Proc. of World Renewable Energy Congress V, Part III:1595-1598.

Kritchman, E.M., A.A. Friesem and G. Yekutieli, 1979. Efficient Fresnel lens for solar concentration. Solar Energy 22: 119-123.

Leutz, R., A. Suzuki, A. Akisawa and T. Kashiwagi, 1999. Design of nonimaging Fresnel lens for solar concentrators. Solar Energy 65: 379-387.

Mihalakakou, G., A. Ferrante and J.O. Lewis, 1998. The cooling potential of a metallic nocturnal radiator. Energy and Buildings 28:251-256.

Niachou, A., K. Papakonstantinou, M. Santamouris, A. Tsangrassoulis and G. Mihalakakou, 2001. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings 33: 719-729.

Santamouris, M., Mihalakakou, G., A. Argiriou and D.N. Asimakopoulos, 1995. On the performance of buildings coupled with earth to air heat exchangers. Solar Energy 54:375-380.

Tripanagnostopoulos, Y., D. Tzavellas, I. Zoulia and M. Chortatou, 2001. Hybrid PV/T systems with dual heat extraction operation. In Proc. 17th PV Solar Energy Conference, Munich, 22-26 Oct: 2515-2518.

Tripanagnostopoulos, Y., Th. Nousia, M. Souliotis and P. Yianoulis, 2002. Hybrid Photovoltaic/Thermal solar systems. Solar Energy 72: 217-234.

Tripanagnostopoulos, Y., M. Souliotis, R. Battisti and A. Corrado, 2003. Application aspects of hybrid PV/T solar systems. In Proc. (CD-ROM) ISES Solar World Congress 2003, Goteborg, Sweden, 4-19 June.

Tripanagnostopoulos, Y., M. Souliotis, J.K. Tonui and A. Kavga, 2004. Illumination aspects for efficient greenhouses. Presented in Greensys2004 Int. Conference, Leuven, Belgium, 12-16 Sep. 2004.

Tsangrassoulis, A., M. Santamouris and D. Asimakopoulos, 1996. Theoretical and experimental analysis of daylight performance for various shading systems. Energy and Buildings 24:223-230.

Zondag, H.A., D.W. De Vries, W.G.J. Van Helden, R.J.C. Van Zolingen and A.A. Van Steenhoven, 2002. The thermal and electrical yield of a PV-Thermal collector. Solar Energy 72:113-128.

Zondag, H.A., D.W. De Vries, W.G.J. Van Helden, R.J.C. Van Zolingen and A.A. Van Steenhoven, 2003. The yield of different combined PV-thermal collector designs. Solar Energy 74:253-269.