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Effect of Nanocoating (CuO Nanoparticles) on the Performance of Solar Evacuated Tube

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Abstract: In domestic solar water heating solar evacuated tubes have been widely used. Enhancement of solar energy absorption is the demand of time and CuO nanoparticles on account of their potential uses mainly in the field of solar energy applications. Cost effective sol-gel method is applied to synthesize CuO nanoparticles on solar evacuated glass tube. The synthesizing initiated from Cupric Acetate with the colloidal solution in water. A thin film has been prepared at room temperature nearly at 30 to 38 °C. The synthesized thin film had been annealed at 300 °C for one hour to give uniform grain structure and good surface morphological properties. For the structural study, the film was characterized by XRD-X-Ray diffraction, SEM-Scanning Electron Microscopy & TEM-Transmission Electron Microscopy. To exhibit the optical behavior of CuO nanoparticles on solar evacuated glass tube, UV-visible spectrum has been performed. By the calculations of an effective mass model, the size of particles determined as 2.26 nm, which supported and justified the TEM analysis. Coated CuO nanoparticles on borosilicate evacuated glass tube has been installed as a domestic solar water heater and working satisfactorily to generate hot water. For solar water heating system (domestic) application of nanotechnology is a novel concept. To develop durable nanocoating on 1800 mm long solar evacuated borosilicate glass tube itself it was a challenge. In this research it is shown that coating is working satisfactorily with energy enhancement. This paper opens the door for new nanocoating developments opportunities.

Keywords: Evacuated tube, XRD, SEM, TEM, CuO nanoparticles

1. Introduction

CuO nanoparticles have been popular due to mechanical, electrical properties. They can be synthesized via several ways, wet chemical and physical routes with minimum concerned of biological methods [1–3]. Nanostructures of CuO different in shape, size and surface morphology should be synthesized with different precursors-copper nitrate and copper chloride by executing different heat treatment methods [4]. Since it has higher solar absorptance and a lower thermal emittance, CuO is attractive as a selective solar absorber. This unique characteristic also preferable as semiconductor and because of considerable band gap, right now it is highly useful for effective photo-thermal conversion devices [5,6]. At room temperature the sol-gel synthesis process can produce materials. and can synthesize almost all kinds of materials, co-synthesize two or more materials. At the same time, precisely it can regulate the microstructure of the final film developed [7–9].

In the case of any synthesis process substrate plays a significant role for the stability of developed film and its optical and electronic properties as well. On borosilicate glass substrate CuO nanoparticles have been deposited by easier and economical dip coating synthesis method [10]. Developed nanoparticles confirmed by XRD, SEM, TEM,

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and UV-VIS analysis. With effective mass model calculation, it is confirmed and concluded that the synthesized CuO nanoparticles are of 5 to 7 nm in the size [11,12]. On actual borosilicate glass tube of 1800 mm long and 47 mm in diameter, solar evacuated tube collector with the help of same pattern and process CuO nanostructured film as an absorber has been developed. The nano film shown very good absorptance and the temperature of the water filled raised inside the tube. This paper reveals the possibility that CuO nanoparticles can be used as an absorber film, improving absorptance and can contribute to energy enhancement & photo-thermal conversion.

2. Experimental

For better optical properties the CuO nanoparticles synthesis is of controllable in shapes, size & surface is very much essential. CuO nanoparticles thin film is developed on the borosilicate glass in actual used for solar water heating. The primary solution is prepared from 250 gm powder of Cupric Acetate monohydrate $\{(CH_3COO)_2Cu.H_2O\}$ and the precursor dissolved in triple distilled water & acetic acid & with a proportion of 1:1. The solution has been stirred at 320 rpm for 1.2 hours at 165 °C, until cupric acetate complete dispersion. Firstly, borosilicate glass has been cleaned by warm distilled water and cleaning agent mixture, then placed in acetone bath for almost 1 hr. Further it is cleaned by an air pressure cleaner & in oven set to be dry at 150 °C for 1.5 hours. The developed thin film on glass substrate at constant speed of 3 cm/min and sample soaked in sol minimum for 2 minutes [13,14].

The developed film annealed at 250 °C for 1 hour for uniform grain structure. Morphological study has been carried out for CuO thin film coated on glass substrate was analyzed by X-ray diffraction (XRD) Model: Xpert MPD, Make: Philips, Holland. For XRD and crystallography, the Scherrer formula has been applied which relates the nanoparticles size, or crystallites or polycrystallites, sub-micrometer particles in a solid to the peak broadening in a diffraction pattern. The size of the particle calculated from FWHM- Full-Width at Half Maximum for XRD lines by using Debye– Scherrer formula [15]. For UV-Vis absorptance measurement was depicted by Lambda 19, Make: Perkin Elmer, U.S.A Shimadzu UV-300 spectrometers.

SEM works in certain voltage range between few hundred kV to 30 kV. In the present work, we have used the field emission scanning electron microscope XL 30 ESEM with EDAX: Resolution: up to 2; Acc. voltage: 30 kV; Magnification: up to 2,50,000x at SICART, Laboratory, Vallabh Vidyanagar for characterizing the microstructure of the glass samples (few portions of the calcined sample at 200 °C). With the help of the image, it is very much clear that the structure is like a honeycomb film, including the islands over the developed surface.

For TEM analysis the specifications of the equipment is, Model: Tecnai 20, Make: Philips, Holland with S-TWIN objective lens for high resolution, while maintaining high tilts (maximum 40°) & a comp stage for accurate specimen control and exceptional mechanical stability, where used to capture to achieve extremely high-resolution (Electron source:- W emitter and LaB6, accelerating voltage:- 200, objective lens:- S- TWIN, point resolution: 0.27 nm, line resolution : 2.0 nm or better, magnification: 25x to 750000x or higher, Single tilt holder with CCD Camera, SICART, Vallabh Vidyanagar-Gujarat)

3. Results and Discussion

3.1 XRD Analysis

The Scherrer formula, crystallography & X-ray diffraction relates the size of nanoparticles developed. The sub-micrometer particles, in a solid for the peak broadening in the diffraction pattern. The full-width at half maximum (FWHM) of XRD lines by using the Debye– Scherrer formula the grain size was calculated as in Equation 1.

$$P = \frac{k\lambda}{\beta \cos\theta} \quad (1)$$

In Equation 1, k = dimensionless shape factor, P = mean size of the ordered domains, almost equal to unity. The shape factor value is about 0.9 and varying with the actual shape of the crystallite, k = X-Ray wavelength (1.54 Å), b = Full width half maxima, h = Bragg Angle. By using Equation 1, the grain size derives is 15.9 nm, here peak 101 (Fig. 1) is considered as the main peak and lattice parameters are c= 5.2163 Å, b = 3.2398 Å & a =3.2398% Å, using the Powder-X software.

3.2 SEM Analysis

SEM [16] uses electrons in place of light to create an image with several advantages. The SEM does have a huge depth of field and allows a large area of the sample under focus at a time. Electron beam from the electron gun is focused under vacuum conditions irradiate the CuO nanoparticles coated on borosilicate glass. The beam of electrons is passing through a positively charged several components like, electrodes, condenser lenses, scan coils and objective lens. The final focusing of the beam is to be done by objective lens on the sample surface. These lenses are magnetic and deflect the electrons and focusing them properly. A representative SEM image for a CuO nanoparticles is given in Fig. 2.

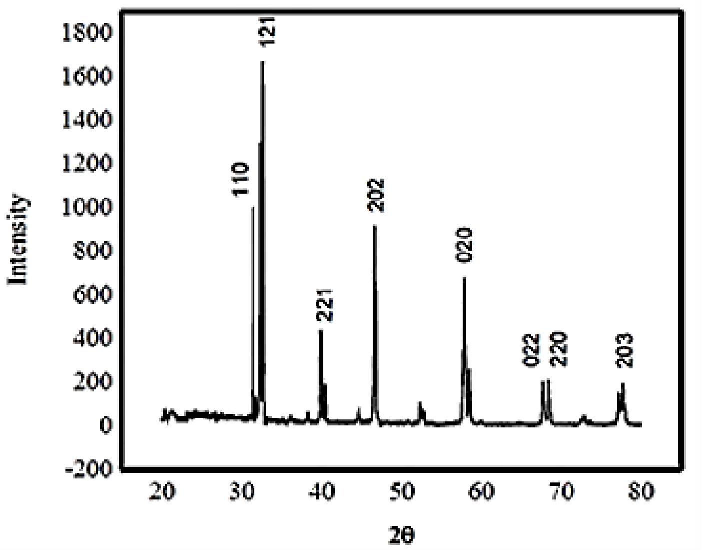

Fig. 1 - XRD pattern of CuO nanoparticles

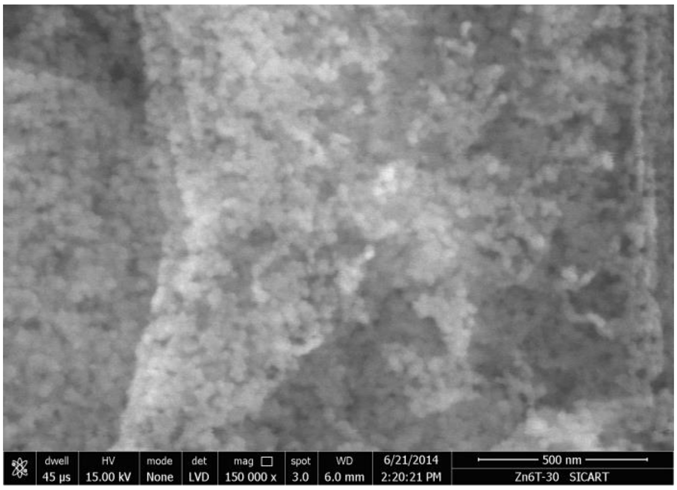

Fig. 2 - SEM micrograph of CuO nanoparticles

3.3 TEM Analysis

TEM micrograph proven very much essential to see nanostructure formation at atomic scale with maximum potential magnification of 1 nm. TEM provides compositional, crystallographic, and morphologic information of selective absorber coating [17]. Fig. 3 shows a TEM of CuO nanoparticles developed on a borosilicate glass substrate. The image shows particle sizes in several blocks, nearer to approximately ~5 nm. It clearly depicts uniform growth of CuO nanoparticles on the borosilicate glass substrate through dip coating deposition. TEM shows that, particles developed are of nano spherical. This large exposing surface area leads CuO nanoparticles most favorable in solar energy absorption & effective heat transfer.

3.4 UV-Vis Spectroscopy Analysis

On the principle of molecular orbitals UV–Vis spectroscopy is working. Individual molecule does have its own molecular orbitals and they are developed by either addition or subtraction of their concerned atomic orbitals. They are also known as bonding and antibonding orbitals. In fig. 4 an overall trend of the results is that shift drop in absorbance observed in the UV–Visible spectrum toward shorter wavelengths a lower particle size. For the range of 300 to 365 nm absorptance dip is observed from 3.3 to 0.25 & for remained range length almost absorption remains constant. The wavelength determines the bandgap E_g of the CuO nanoparticles is as in Equation 2.

$$E_g = \frac{hc}{\lambda} \quad (2)$$

Where, λ is a wavelength absorbed by the sample, and C is the speed of light.

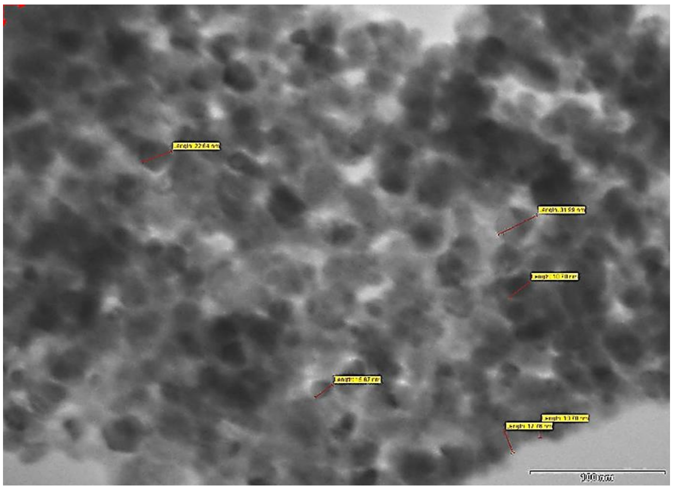

Fig. 3 - TEM micrograph of CuO nanoparticles

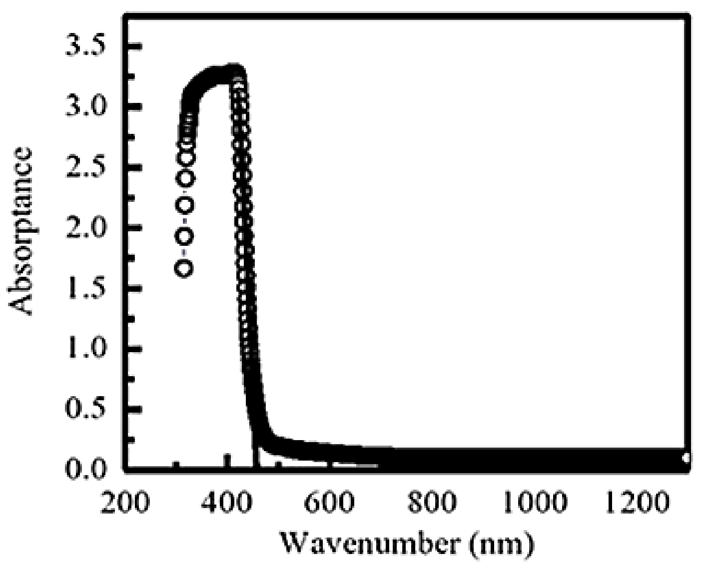

Fig. 4 - UV-Vis absorption spectra of CuO nanoparticles synthesized on glass substrate

As stated in Equation 3, this equation is used to calculate the size of particle. By the UV-Vis experimental absorption spectrum the particle size has been calculated. Equation 3 is based on effective mass model, where, E_g *(bulk)* = band gap energy of the bulk Cu at ambient temperature, 3.88×10^{-9} J, E_g= band gap energy of the nanoparticles, r = radius of the particle ,h= Planck's Constant, 6.625×10^{-34} J.s, mh^* = effective mass for a hole in CuO, me^* = effective mass of band electron in CuO, ε_0= free space permittivity, ε = relative permittivity of CuO, e = elementary charge.

$$Eg = Eg(bulk) - \frac{h^2\pi^2}{2r^2}\left(\frac{1}{me^*}+\frac{1}{mh}\right)+\frac{1.8e^2}{4\pi\varepsilon\varepsilon or}-\frac{0.124e^4}{h^2\left(4\pi\varepsilon\varepsilon o\right)^2}\left(\frac{1}{me^*}+\frac{1}{mh}\right) \tag{3}$$

3.5 Evacuated Tube Collector (ETC) Set Up with CuO Nanostructured Absorber Coating

In conventional ETC there are three layers AlN, SS-AlN & Cu, where Cu is the responsible for effective heat transfer from glass to water. The model shown in Fig. 5, which is CuO nanoparticles coated will serve for absorption as well as transferring heat to water. In terms of thermal conductivity copper nanofluids have been proved excellent and eventually thermal efficiency improves. In TEM analysis the generated nanoparticles are nearly of 5 nm & ultimately lead towards significant enhancement in solar radiation absorption film surface area. Fig. 5 is of experimental set-up of CuO nanoparticles coated solar evacuated tube collector. Specifications give an overall picture of experimental set up is tabulated in Table 1.

The experimental performance has been analyzed by the measurement of various parameters. The characteristic curves include instantaneous efficiency, solar radiation intensity and water temperature of the set up itself. In Fig. 6 characteristic curves give an idea whether the performance of CuO nanoparticles coated evacuated tube.

Fig. 5 - CuO nanoparticles coated ETC experimental set up

Table 1 - Specifications of ETC

Specification	Value
Outer Dia.	58 mm
Inner Dia.	47 mm
Length	1800 mm
Weight	2 kg (Approx.)
Material	Borosilicate glass tube - 1.6 mm thick
Tilt angle	30°
Absorber Coating	CuO nanoparticles
Absorptance & emissivity	~94% & ~6%
Vacuum	5×10^{-3} Pascal
Heat loss	0.8 W/m^2 °C
Working fluid	Water
Storage tank specifications	1. Material - GI coated sheet 2. Insulation - Rock wool

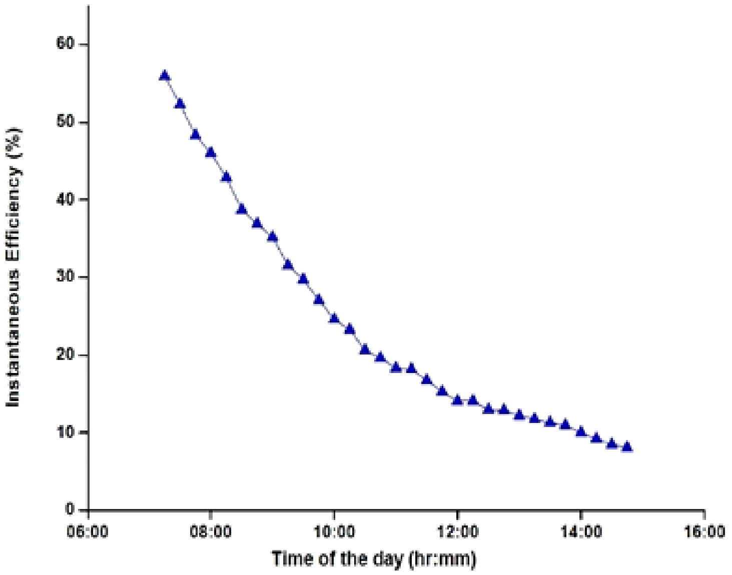

Fig. 6 - CuO nanoparticles coated solar evacuated efficiency vs daytime

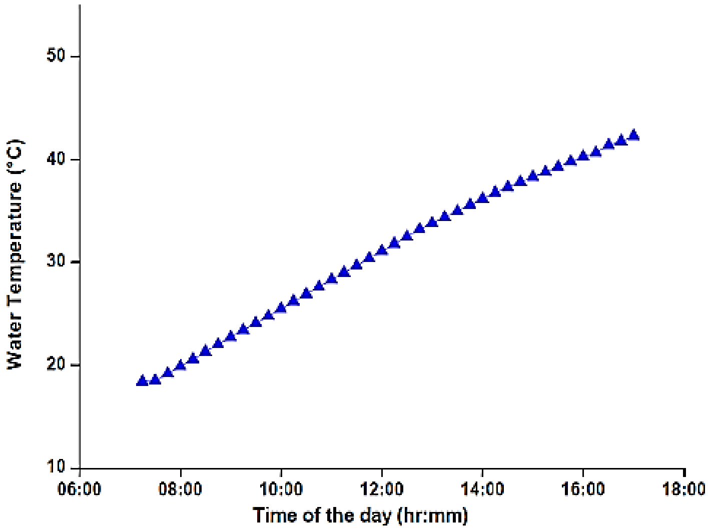

Fig. 7 – ETC instantaneous tube water temperature vs daytime

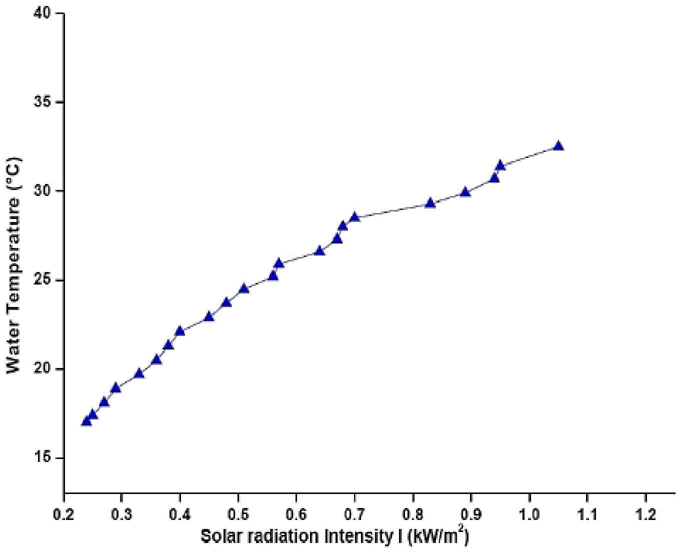

Fig. 8 – Performance curves of water temperature radiation intensity (I)

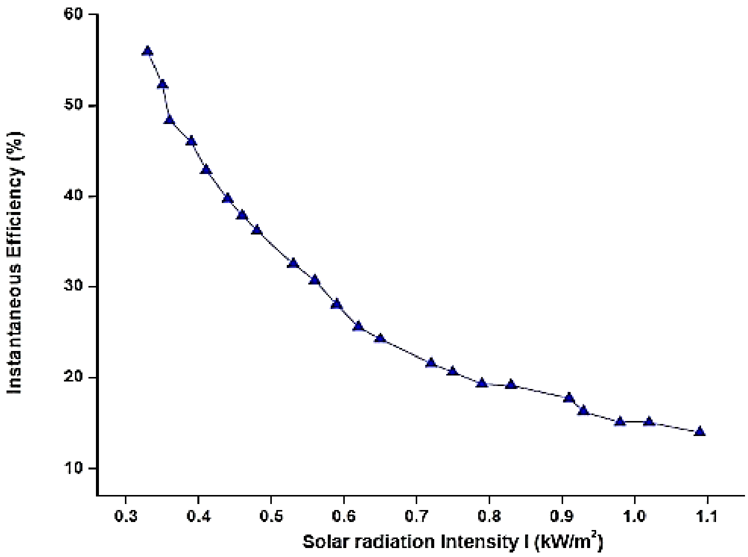

Fig. 9 – Performance curves of instantaneous efficiency vs solar radiation intensity (I)

Characteristic curves give the real picture and confirm whether does it have satisfactory performance or not? Above given all graphs have been plotted on the base of parameters measured during the performance. As per literature review all above graph patterns are matching with previously studied [18]. The maximum water temperature observed is nearly 45 °C noted in the evening at 17:15 hours, which is higher than any conventionally available model in the market. Instantaneous efficiency is having decreasing pattern Fig. 7 and Fig. 9 plotted with respect to the time of the day and solar radiation. Highest efficiency reported is 57.5 % in the morning at 07:00 hours and 0.35 Kw/m^2 solar radiation. Fig. 8 indicates the performance of water temperature with respect to solar radiation absorber by CuO nanoparticles. Nearly it is in-line with the rise of solar radiation throughout the day.

4. Conclusion

CuO nanoparticles successfully synthesized on glass substrate of borosilicate. The results revealed optical characterization and thin film development observed in XRD, SEM, TEM & UV-Visible spectrometry. The derived data confirm the CuO nanoparticles generated are of the desired size. This study explored new directions of photo-thermal conversion for solar water heating systems used for domestic purpose. Characteristic curves revealed that the performance of nanocoated film is very much better and have chances to replace existing solar ETC.

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