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RESEARCH ARTICLE - PHYSICS

The Optimum Tilt Angle of Compound Parabolic Solar Thermal Concentrator in Baghdad

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Abstract

The Compound Parabolic Concentrator (CPC), among all types of concentrators, is designed to capture solar radiation and maintain it at a relatively high temperature. For solar power systems and high-temperature solar thermal systems, the CPC may be the best choice. This paper theoretically analyzes a two-dimensional compound parabolic solar thermal concentrator design model. The aim of this study was to determine the optimal values for the solar incidence angle. The CPC thermal system's design equations were simulated using MATLAB software. The solar incidence angle on the solar panel was calculated as an average for each month, using four tilt angles: 15°, 30°, 45°, and 60°. Over a 12-month period, the incidence angle was calculated between 5:00 AM and 6:00 PM. The best results obtained were in September, where the solar incidence angle reached 0.8 degrees, the lowest value at a tilt angle of 30°. In February, the incidence angle was 1.8 degrees at 12:00 PM with a tilt angle of 45°. In July, the incidence angle reached 3.6 degrees at 12:00 PM with a tilt angle of 15°.

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Keywords: Compound Parabolic Concentrator; Angle of Incidence; The solar constant; Tilt Angle; Solar Thermal Collector.

1. Introduction

Energy forms the basis of human life, as it is essential for sustaining all biological processes and powering technological advancements [1]. Iraq is one of the wealthiest nations in terms of solar energy, which is a renewable and environmentally benign energy source [2]. Solar concentrators, especially parabolic ones, have gained considerable attention in recent years. Compound parabolic concentrators (CPCs) are excellent non-imaging reflective concentrators, utilizing the edge ray principle, suitable for both thermal and electrical applications [3]. Furthermore, it can be used indirectly for heating purposes by employing solar thermal collectors. In this way, solar water heating is a somewhat easy and effective way to capture and use solar energy. Because solar thermal collectors are typically 4–5 times more efficient than photovoltaic systems, they are significantly less expensive per unit of energy generated [4]. The solar collector is said to be the most important part of modern heating systems. Since the middle of the 1960s, the compound parabolic concentrator (CPC), a component of non-imaging optics, has been seen as a very attractive and promising choice for solar energy concentration and illumination [5]. It is the perfect solar energy collector because it minimizes loss while gathering and concentrating a greater area of sunlight onto a smaller area [6]. A receiver is positioned along the axis of symmetry of the two parabola parts that make up the CPC solar collector. Numerous studies on CPC have been published in the literature. These studies have used a variety of receiver types, working fluids, and geometric layouts to enhance the optical and thermal performance of the device [7]. The solar collector system was heated using the CPC and was exposed to both direct and reflected solar light. Regarding many parameters that were used to assess the thermal behavior for solar air heater's, including collector length, wind speed, and air mass flow rate [8]. The reflecting surface of a three-dimensional (3D) CPC is formed by rotating the cross-section of a 2D CPC about the CPC axis [9]. Provided an experimental and numerical study on a solar concentrator to characterize the heat and fluid flow behavior inside a CPC collector. The results show that the proposed technology was able to supply stable temperatures for industrial applications. Gu [10]. Instead of continuously following the sun, compound parabolic collectors (CPCs) require only sporadic tilt adjustments and allow for a broad acceptance angle that concentrates incident sunlight [11]. There is little research on compound parabolic collectors, or CPCs. For example, Li et al. [12]. Over time, a number of authors have published research on the application of CPC for mid-temperature process heat [13]. Rabl and Winston suggested a CPC with a restricted exit angle to improve solar absorption of receivers, since in a CPC-based system, the incident angle on the absorber for radiation reflecting from lower part of parabolic reflectors is considerable large, and this part of solar radiation cannot be efficiently absorbed by plate receivers [14].

2. Compound Parabolic Solar Thermal Concentrator

The CPC can reflect all of the radiation to the absorber over a relatively large range of angles [15]. Several CPC collector topologies have been proposed and studied by various researchers over the past few decades. In order to generate electrical and thermal energies simultaneously [16]. Additionally, studies have shown that CPC solar collectors in conjunction with double-layered evacuation glass tubes are used in many solar systems because to the vacuum space's ability to reduce convective and conductive heat losses [17]. The CPC consists of two equivalent reflectors, a target surface at the exit aperture receives incoming sun rays from two focusing parabolic reflecting surfaces, which are part of the CPC's, basic geometry depicted in Fig. (1). The left and right segments of the CPC are segments of two parabolas, with the receiver situated between their focus points. An angular range known as the acceptability half-angle tilts the parabolic segments' axes away from the CPC axis (Masood et al., 2021b) [18]. CPCs are essentially composed of three components:

I. Cover: A transparent cover is the best option insulating material that permits solar radiation to pass through to the reflector and receiver, while minimizing the transmission of thermal radiation from the receiver. It should also allow for a high transmission of solar radiation, is cost-effective, and possess long-lasting durability.

II. Reflector: The maximum reflectivity is ideal for solar concentrator reflectors. Focusing the receiver, which is located at the system focus, with the direct solar energy, is its purpose.

III. Receiver: To effectively transfer the absorbed heat to the heat transfer fluid, the CPC receiver should be constructed of metals with high thermal conductivity and have the highest absorptance for solar radiation. Specialized solar-selective surfaces must be applied to receiver materials because the majority of them do not have extremely high absorptance [18].

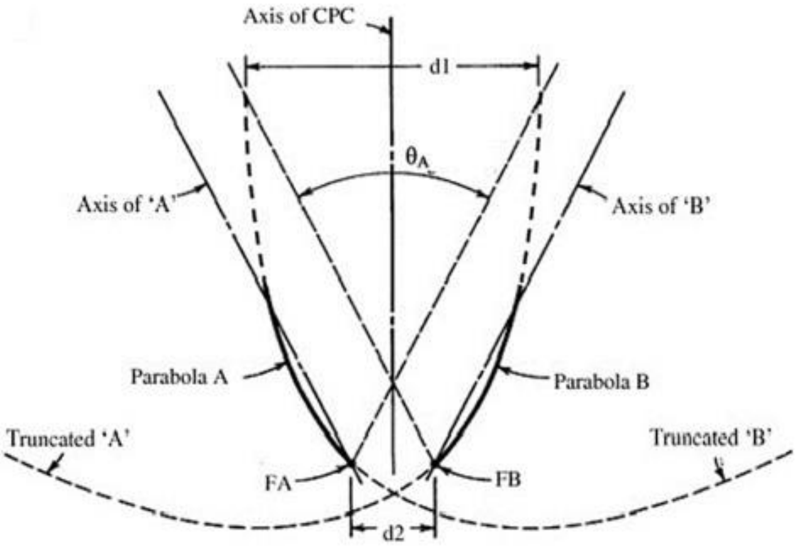

Fig. (1): Basic geometry of 2D CPC [18].

3. Design of the Compound Parabolic Concentrator

The solar rays entering the concentrator at maximum acceptance angle are reflected tangentially to the absorber surface. The maximum acceptance angle is given by [18]:

$$\tan\,(AOI) = \frac{D+d}{2H} \quad (1)$$

Where D is the entrance aperture width, d the absorber width and H the concentrator height of CPC. The extraterrestrial solar radiation is calculated using the following equation [17]:

$$H = H_0(1 + 0.034COS((360.dn)/365.25)) \quad (2)$$

Where H_0=1353 W/m^2 which represent the solar constant.

The variation sunlight in irradiation is ± 3.5 %, where dn is the day of the year. The following equation uses air transmittance calculations to get at normal incidence, the beam solar irradiance (Hb,N) [19]:

$$Hb, N = H(A_{0+}A_1 EXP(-KAM)) \quad (3)$$

A_0, A_1 and K are constant parameters. The following formula is used to determine the diffuse solar irradiance (Hd,h) on a horizontal surface [19]:

$$Hd, h = Hcos(\,Z_s)[0.2710 - 0.2939(A_{0+}A_1 EXP(-KAM))] \quad (4)$$

The following equation describes how the radiation is dispersed worldwide over a flat surface using the information above [20]:

$$Ht = Hd, h + Hb, N \quad (5)$$

Where Ht is radiation from the entire world. On a tilted surface, at an angle of incidence (AOI), the beam solar incident irradiance is calculated by [20]:

$$HB = \mathrm{Hb, N} \cos A0I \quad (6)$$

4. Results and Discussion

The theoretical results were compared with the experimental results, and a close alignment was found, where the optimal tilt angles experimentally were the closest to the tilt angles used theoretically. There are several external conditions that affect the performance of the Compound Parabolic Concentrator (CPC), including radiation intensity, temperature, wind speed, and weather conditions. Fig. (2) illustrates the effect of time on solar incidence angles using tilt angles on the solar panel in January using a MATLAB program. Four different tilt angles were tested: 15°. 30°, 45°, and 60°. It was observed that the values started high at the beginning of the day, with the increase beginning at 5:00 AM. The values then decreased until 12:00 PM. The optimal tilt angle was 60° in January, as it showed the lowest solar angle of incidence at 12:00 PM was 9.29. This indicates that a lower solar angle of incidence results in a higher concentration of sunlight on the solar panel. In summary, the 60° tilt angle was the most effective, as it allowed for higher concentration of sunlight at midday, thereby increasing the efficiency of the solar system in January. In February, the optimal tilt angle was 45°, where the value of the angle of incidence at 12:00 PM was 1.80 degrees. This was the lowest value compared to the other angles and the most concentrated, as shown in Fig. (3). In March, the optimal tilt angle was 30°, where the angle of incidence at 12:00 PM was 5.46 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (4). In April, the optimal tilt angle was 30°, where the angle of incidence at 12:00 PM was 6.45 degrees. This was the lowest value and the highest concentration, as shown in Fig. (5). In May, the optimal tilt angle was 15°, where the angle of incidence was 0.9°. This was the lowest value and the most concentrated for this month, as shown in Fig. (6). In June, the optimal tilt angle was 15°, where the angle of incidence was 5.28 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (7). In July, the optimal tilt angle was 15°, with an angle of incidence of 3.69 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (8). In August , the optimal tilt angle was15°, with an angle of incidence of 3.60 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (9). In September , the optimal tilt angle was 30°, with an angle of incidence of 0.82 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (10). In October , the optimal tilt angle was 45°, with an angle of incidence of 3.61 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (11). In November , the optimal tilt angle was 45°, with an angle of incidence of 6.21 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (12). In December , the optimal tilt angle was 60°, with an angle of incidence of 3.96 degrees. This was the lowest value and the most concentrated for this month, as shown in Fig. (13). Here, ‘Tm’ in the shapes below represents the tilt angles.

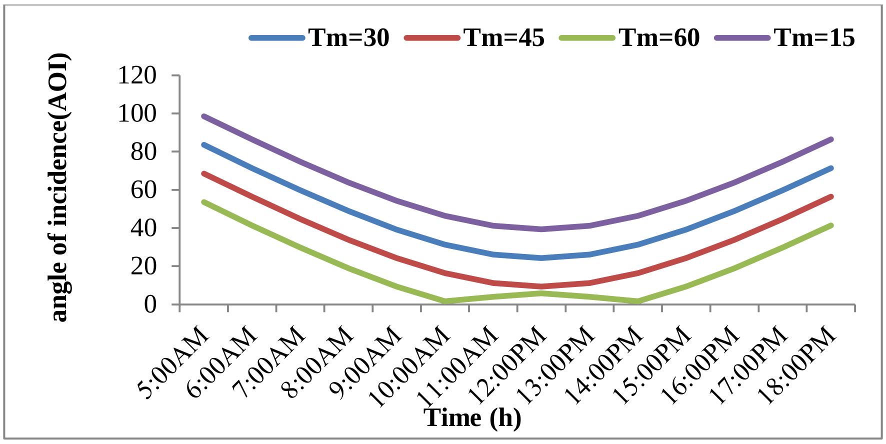

Fig. (2): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in January.

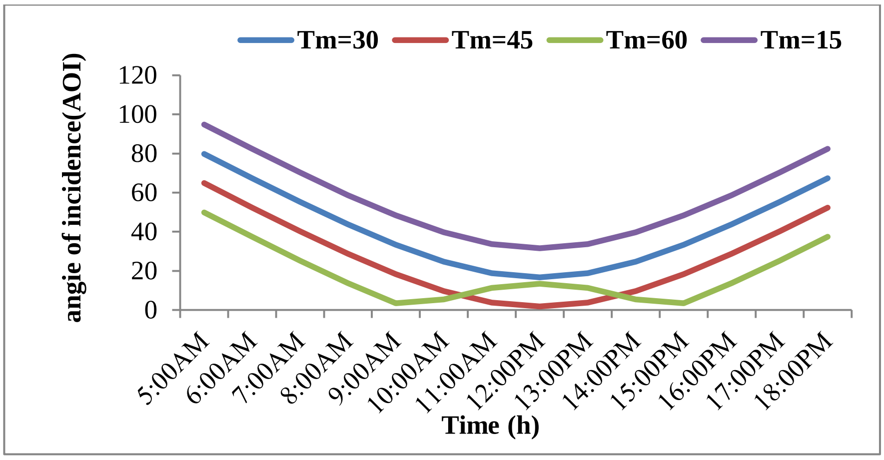

Fig. (3): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in February.

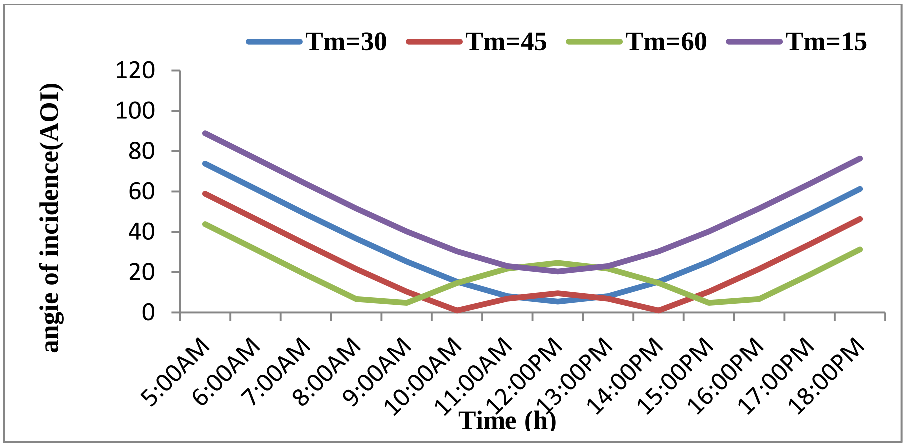

Fig. (4): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in March.

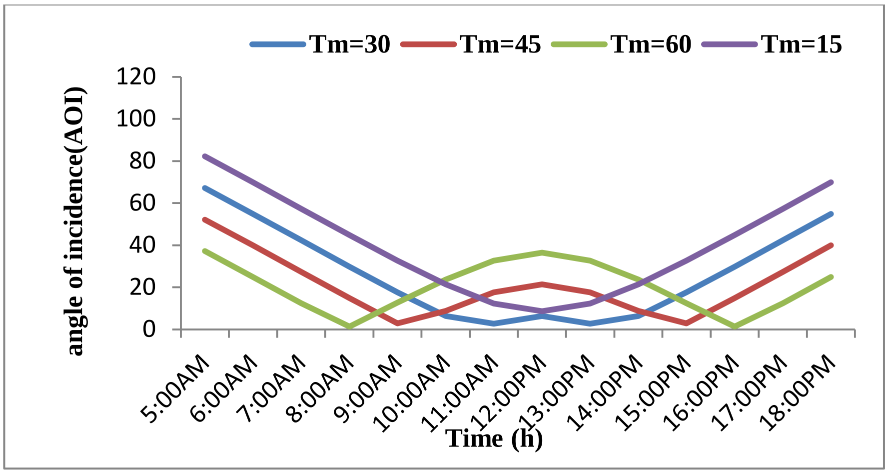

Fig. (5): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in April.

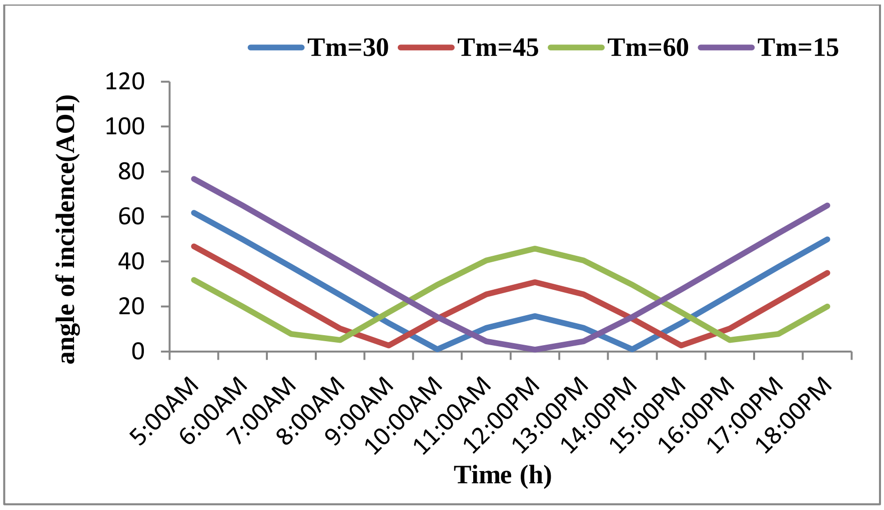

Fig. (6): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in May.

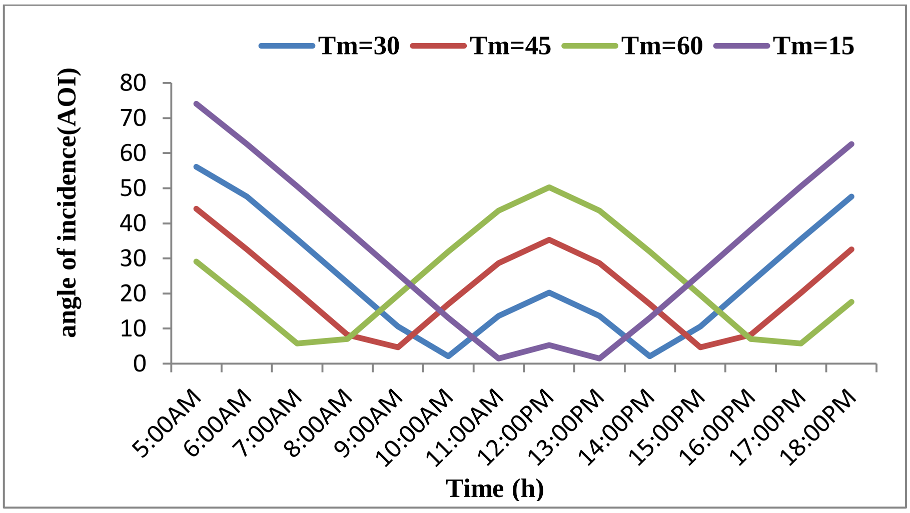

Fig. (7): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in June.

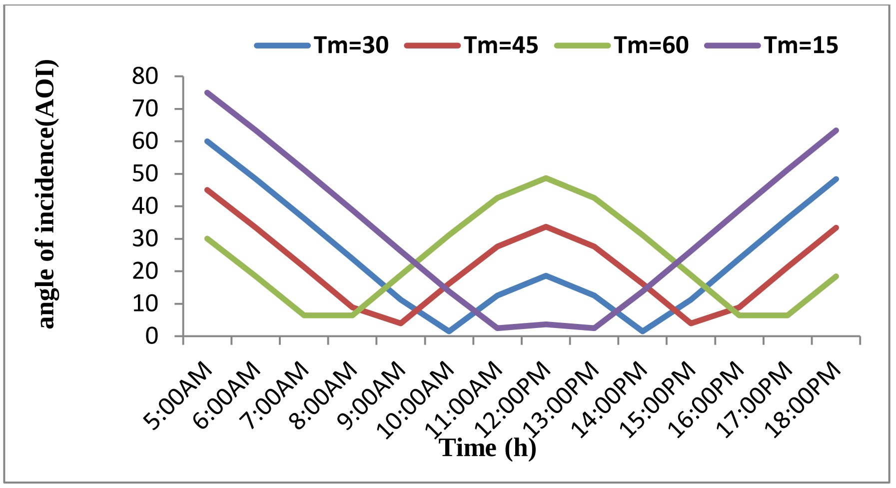

Fig. (8): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in July.

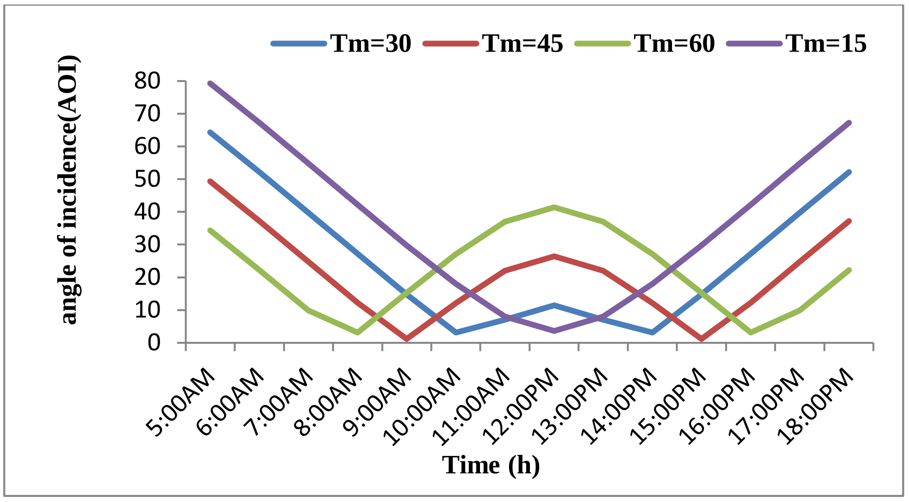

Fig. (9): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in August.

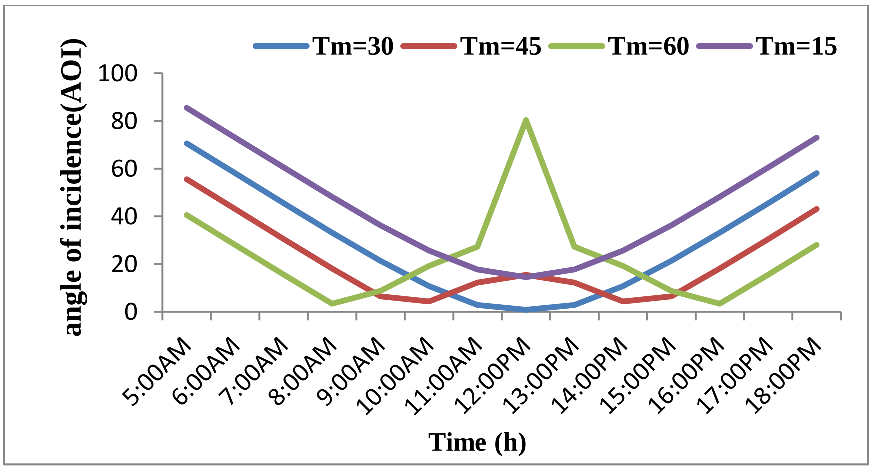

Fig. (10): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in September.

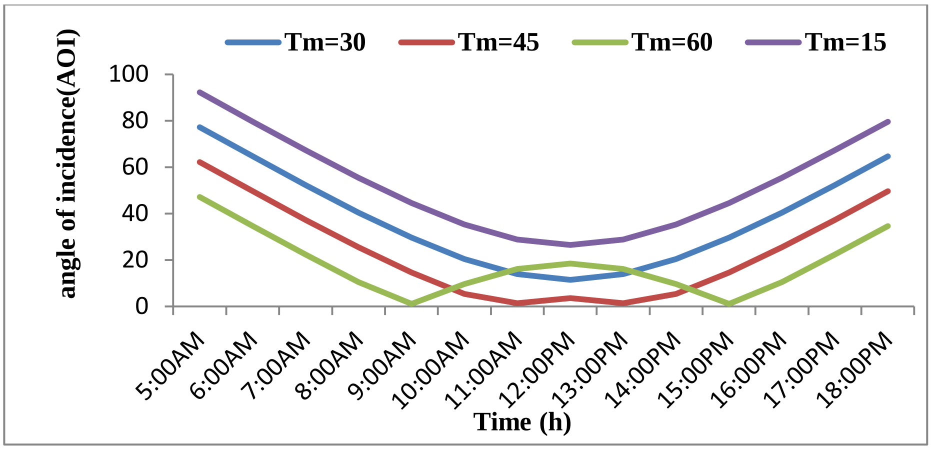

Fig. (11): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in October.

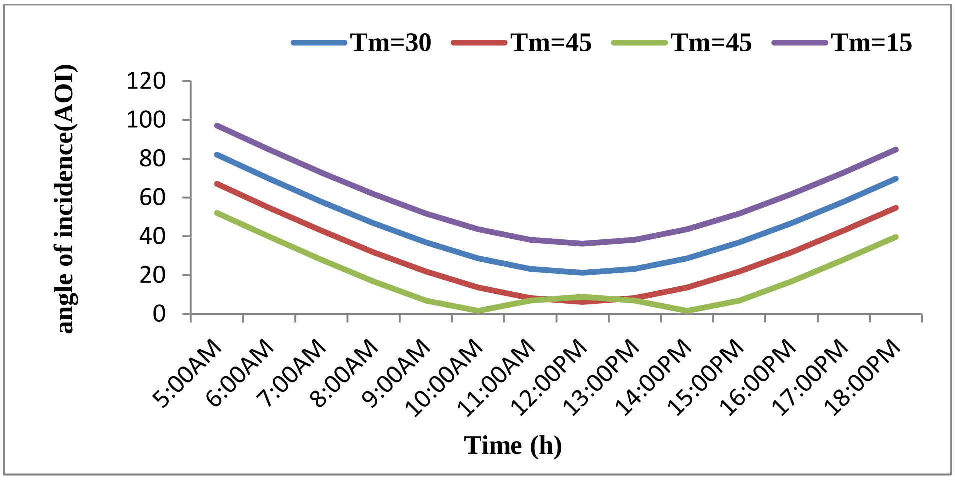

Fig. (12): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in November.

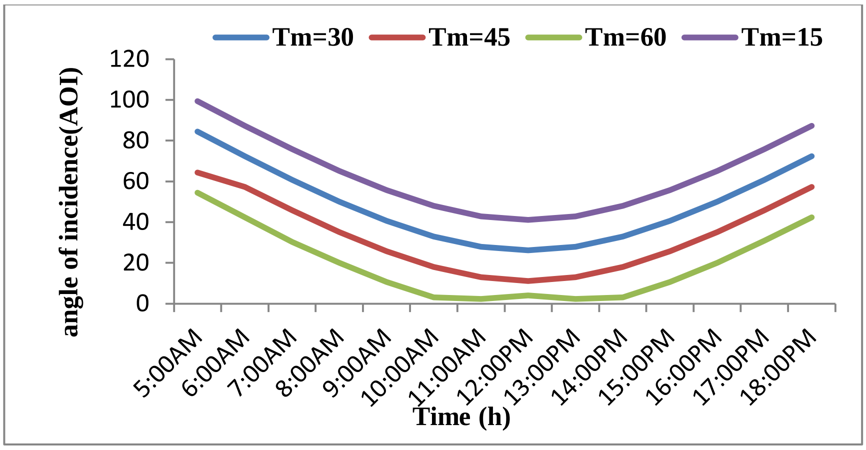

Fig. (13): The effect of time on the solar angle of incidence using tilt angles (15°, 30°, 45°, and 60°) in December.

4. Conclusions

Based on the results, the optimal angle for achieving perpendicular alignment occurs when the solar zenith angle equals the tilt angle, ensuring that solar rays fall perpendicularly on the CPC surface. Additionally, the larger the tilt angle (or the closer it is to the perpendicular angle), the greater the concentration of sunlight on the target point, enhancing the effect of perpendicular alignment in that area. This suggests that adjusting the tilt angle can help increase solar energy concentration. The optimal angle in Baghdad ranged between 30° and 45°.

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