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Design of an Absorber Plate for Solar Air Dryer Using Nickel Oxide Nano Particle Coating

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ABSTRACT
Energy, whether non-renewable or renewable, is vital for the survival of all the living things on this planet. The growing human population all over the world has increased the demand for energy resources and energy from the sun has earned significant interest in recent times. However, the efficiency, cost, and longevity of the absorber plates that are commercially used have been a common issue. In this paper, an attempt has been made to make an absorber plate for a solar dryer and make better use of renewable solar energy. The goal is to fabricate an absorber plate capable of transferring heat and low in price for the people of Bangladesh. For this, similar past works were studied thoroughly and a literature review was made for a reliable comparison. From there, several coating materials were shortlisted as a candidate for this research project. After observing that Nickel oxide nanoparticles serve as the best coating material for this work, simulations of the computational model were performed using Excel spreadsheets. Based on simulation results, the plan is to fabricate an affordable plate and analyze the performance by different characterizations for applying in practical uses such as solar dryers, solar stills, etc. The computational model was validated with the work of similar research which will be discussed below.

Keywords: *Solar air dryer, Absorber plate, Nickel oxide nanoparticles, Simulation.*

1. INTRODUCTION

Renewable energy or clean energy sources supply only 15% of our energy demand so far and are seeming to be more and more important for countries day by day [1]. With the conventional, non-renewable energy sources running out gradually over the past decades, solar energy has been proven as alternative energy for a long time. In 2020, 713970 MW of solar energy capacity was produced all over the world and this number has been growing over the past several years [2].

A solar dryer is a device that uses solar energy to heat and dry substances like food. The heat decreases the relative humidity of the air and so it can hold more moisture. Warm, dry air flowing through the dryer carries away the moisture that evaporates from the surfaces of the food. Solar dryers are of two types: Direct and Indirect. Figure 1 shows a direct type of solar dryer where the food is exposed to direct sunlight.

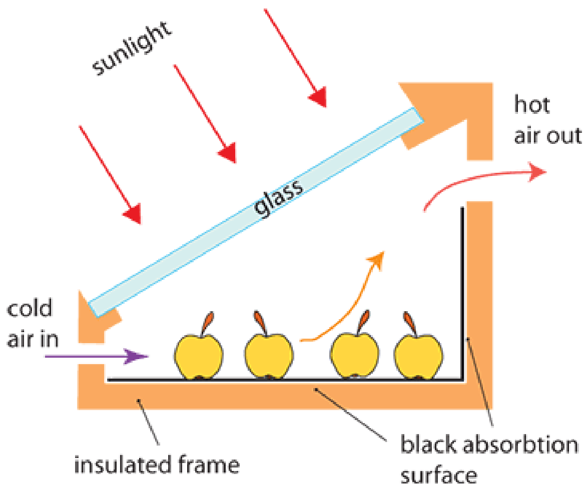

Figure 1 Schematic diagram of a direct solar dryer.

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Figure 2 shows an indirect type of solar dryer where the black surface heats the incoming air rather than directly heating the substances to be dried.

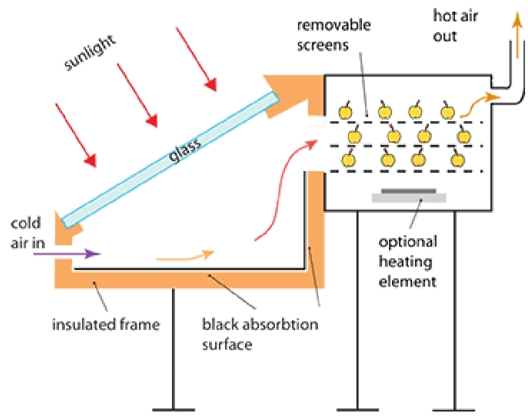

Figure 2: Schematic diagram of an indirect type of solar dryer.

The absorber plate is a common and important part of the devices mentioned above. The purpose of this plate is to absorb a large portion of the incoming solar irradiation energy and transfer it to the circulating fluid passing through internal passageways. This heated fluid can be used for several purposes. These collectors are thermally insulated to reduce heat loss. It is a challenge to collect enough heat using the plate although it often gets corroded due to contact with water and air for a long period.

2. LITERATURE REVIEW

2.1. Related Works

B. Kundu [3] observed the efficiency from different shapes of absorber plates and they found that rectangular and flat shapes of absorber plates are most efficient and have a simple manufacturing process. Around 60 to 70% efficiency was investigated using a flat shape plate by S. Jaisankar *et al.* [4]. The porous or roughened absorber plates having a lower refractive index and higher heat transfer coefficient exhibit better efficiency than smooth plates due to lowering the amount of solar reflection from the plate surface [5, 6]. Nanoparticles used as coating materials have shown significant improvement in results compared to conventional coatings. Srividhya *et al.* [7] observed that nano-NiO coating shows better results in comparison with the black chrome coated unit by producing higher outlet temperatures. Kabeel *et al.* [8] integrated a phase change material (PCM) on the absorber plate acted as a thermal storage medium and showed an efficiency of 70%. In another work [9], 5% multi-walled carbon nano-tube (MWCNT) having a thermal conductivity of 3000 W/m K was used as an absorber plate for a solar still and showed an efficiency of 83.7%. However, the fabrication of such solar absorber plates is complicated. The MWCNT needs to embed on the epoxy surface uniformly by the Ultrasonication technique and this technique is expensive to carry out. M. Faizal *et al.* [10] observed that CuO nanofluid was used as a working fluid but its cost is high even though the size of a solar collector can be reduced by using such nanofluids. T. Tesfamichael *et al.* [11] compared the performance between Ni-NiO_x and Ni-Al_2O_3 as a solar absorber plate. They found that the solar absorbance was increased with increasing the angle of incidence of solar radiation for Ni-Al_2O_3 plate. However, it was not the case for Ni-NiO_x absorber plate.

2.2. The Coating Materials

Table 1 below shows the optical properties and the thermal efficiency of the coating materials that were shortlisted for this study and the data obtained by the respective authors.

Table 1. The optical properties and thermal efficiency of the available coating materials from the literature review.

Coating Material	Data obtained	Reference
5% CNT	83.7% efficiency	Abdelal et al. [9]
Phase change material (PCM)	70% efficiency	Kabeel et al. [8]
Black Chrome	α_{sol} = 0.8-0.9; ε_{therm}= 0.01-0.03	Lee et al. [12]
Nickel oxide	α_{sol} = 0.95; ε_{therm}= 0.05	Voinea et al. [13]

2.3. Working Principle of an Absorber Plate

A solar dryer is a device that uses solar energy to dry substances, especially food and it requires a collector or an absorber plate which consists of metallic tubes, a glass cover and a coating that can ensure the maximum possible heat absorptance, α, and a low emissivity, ε. The glass cover will provide insulation and to also reduce convection losses from the absorber plate to the surrounding air. The transmittance, τ, of the glass cover should be ideally close to 1. The tubes will be made of a material with high conductivity and will carry the heat transfer fluid (HTF) which is usually water. In operation, fluid is made to flow into one side of the flat plate (usually at the lower end), and it is then withdrawn on the other side (usually at the upper end) after having been heated to temperatures ranging from ambient up to 120 °C depending on the design). Flat plate collectors can be made for temperatures higher than this but concentrating collectors at some point become more cost-effective. The coating, which is our main goal, can be implemented in many ways to increase the absorptivity further. So, when sunlight falls on the plate, the plate absorbs part of the heat energy and transfers it to the HTF flowing through the tubes, which is air in the case of this present study

2.4. Our Contribution

From the literature review, it was found that the materials needed to make an efficient solar absorber plate are expensive to purchase or embed in most cases. These expensive plates will not be feasible to use in our country. So, the prime goal is to fabricate a cost-effective absorber plate to serve the purposes of this study. The main challenges include the durability and thermal efficiency of the absorber plate, and the cost of the materials. This paper focused on implementing different materials and coatings to make the absorber plate as efficient and cheap as possible.

2.5. Required Equations of the computational model

In this research, the computational model was developed by using the appropriate equations by Dunkle [14]. The analysis was done using an Excel spreadsheet.

Here, the natural parameters' data (solar insolation, ambient air temperature, wind velocity) were obtained from PVGIS for the coordinates of AUST (23.76°N, 090.41°E) [15].

Considering that Tg_i is greater than Ta_i, the partial pressure of inside and outside air is expressed as:

$$Pa_i = exp\left(25.317 - \frac{5144}{Ta_i+273}\right) \quad (1)$$

$$Pa_o = exp\left(25.317 - \frac{5144}{Ta_o+273}\right) \quad (2)$$

Convective heat transfer from the inner surface of the glass to inside air is expressed as:

$$h_{Cgi\text{-}ai} = 0.884\left[(T_{gi} - T_{ai}) + \frac{Pa_i(T_{ai}+273)}{268900-Pa_i}\right]^{1/3} \quad (3)$$

$$Q_{Cgi\text{-}ai} = h_{Cgi\text{-}ai}(T_{gi} - T_{ai}) \quad (4)$$

Radiation heat transfer is expressed as:

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_g} - 1\right)^{-1} \quad (5)$$

$$h_{Rgi\text{-}ai} = \varepsilon_{eff}\sigma\frac{[(T_{gi}+273)^4-(T_{ai}+273)^4]}{T_{gi}-T_{ai}} \quad (6)$$

$$Q_{Rgi\text{-}ai} = h_{Rgi\text{-}ai}(T_{gi} - T_{ai}) \quad (7)$$

The total heat transfer rate is then expressed as:

$$Q_{Tgi\text{-}ai} = Q_{Cgi\text{-}ai} + Q_{Rgi\text{-}ai} \quad (8)$$

The total heat transfer coefficient that considers the effect of both the free convection and radiation, h_{Tba}, is expressed as:

$$h_{Tba} = 5.7 + (3.8 \times v_w) \quad (9)$$

So, the conduction heat transfer coefficient between the absorber plate and the surroundings, h_b, is expressed as:

$$h_b = \left(\frac{L_i}{K_i} + \frac{1}{h_{Tba}}\right)^{-1} \quad (10)$$

The convective heat transfer coefficient between the plate and air mass is expressed as:

$$h_a = 0.884\left[(T_{bi} - T_{ai}) + \frac{Pa_i(T_{ai}+273)}{268900-Pa_i}\right]^{1/3} \quad (11)$$

So, the convective heat transfer between the plate and air mass is expressed as:

$$Q_{b\text{-}ai} = h_a \times (T_{bi} - T_{amb}) \quad (12)$$

The final temperature of the absorber plate can be found by:

$$T_{bf} = \frac{\alpha'_b I(t) + h_a T_{ai} + h_b T_{bi}}{h_a + h_b} \quad (13)$$

where the fraction of solar flux absorbed by the plate is given by:

$$\alpha'_b = \alpha_b(1-\alpha_g)(1-R_g) \quad (14)$$

2.6. Codes/Standards/Guidelines

Since our project deals with the use of metals, these metals, whether waste or excess in amount, need to be discarded in proper ways. For this, some guidelines are needed to be followed. According to the Technical Guidelines on Environmentally Sound Management of Biomedical and Healthcare waste (HCW) [16] provided by the Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal, healthcare waste should be classified and disposed of as given below.

1. Code A: Non-risk HCW

Recyclable waste (14): It includes paper, cardboard, non-contaminated plastic or metal, cans, or glass that can be recycled if any recycling industry exists in the country.

2. Code D: Other healthcare waste

Waste with high contents of heavy metals should normally be treated in specific recycling/ treatment facilities. Alternatively, as for chemical waste, it may be encapsulated. Waste with high contents of heavy metals, in particular mercury or cadmium, should never be incinerated.

3. Color coding system

The application of a color-coding system aims at ensuring an immediate and non-equivocal identification of the hazards associated with the type of HCW that is handled or treated.

3. RESEARCH METHOD

From the perspective of Dhaka city, a costly solar absorber plate will not be beneficial. So, the challenges are the cost, durability, and thermal performance of the absorber plate. So, the objectives were established, which are:

1. To design an efficient and cost-effective solar absorber plate for solar dryers for countries like Bangladesh.
2. To fabricate (if possible) and conduct experimental investigations of the solar absorber plate with the desired coating material.
3. To conduct performance analyses of the newly designed absorber plate by using the Dunkle model [14] and validating the output temperature of this computational model with the work of Srividhya *et al* [7].

For this, previous similar works were studied, and Nickel oxide was selected as the prime candidate because of its low retail price and because its inexpensive and easy embedding technique. Figure 3 shows a flowchart of the methodology that has been followed during this work.

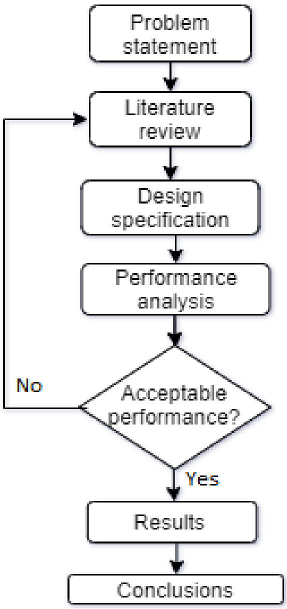

Figure 3 A flowchart of the methodology used in the present study.

4. DESIGN ANALYSIS

The absorber plate can be of many shapes. Mainly, rectangular, trapezoidal, and rectangular profiles with a step-change in local thickness (RPSLT) are used. The absorber plate is made with aluminum. The plate will be further coated with NiO nanoparticles in powder form.

4.1. Design Parameters

The length and breadth of the absorber plate were taken according to the available area of the solar dryer for the plate. However, the thickness of the plate is taken as 4 mm since research [17, 18] showed that 16.5% more production is possible if 3 mm glass thickness is used instead of 6 mm or more glass thickness. The dimensions are shown below in Table 2.

Table 2. The dimensions of the absorber plate.

Parameters	Dimensions (mm)
Length	950
Width	350
Thickness	4

The tilt angle and the azimuth angle in Table 3 for the absorber plate on the solar dryer are optimized from Global Solar Atlas [19] where the longitude and latitude of the location of this present study were placed as inputs (23.76°N, 090.41°E).

Table 3. The geometric parameters of the solar dryer.

Parameters	Value	Unit
Tilt angle, α	23	Degree
Azimuth angle, ψ	180	Degree

4.2. Design Component

Figure 4 shows the preliminary design of the solid model of the absorber plate. This is a flat-type absorber plate. This type is compatible with the solar dryer involved in this study. The base material is aluminum, and it will be coated with NiO nanoparticles. Its dimensions are discussed in Section 4.1.

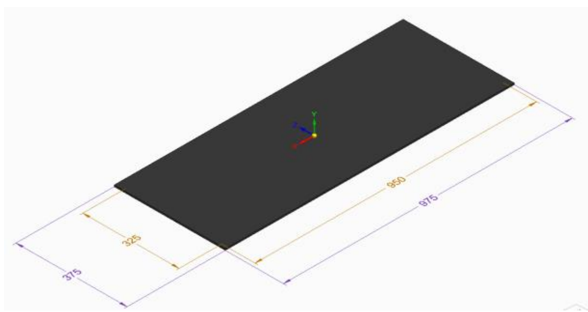

Figure 4: An illustration of the absorber plate.

5. PERFORMANCE ANALYSIS

5.1. Simulation

The simulation works have been done using MS Excel spreadsheets and CodePro to find out the final temperature of the absorber plate. For this, the equations (discussed in section 2.5) and some of the input parameters provided by Dunkle [14] and Johnson *et al.* [20], respectively, were used and implemented in an Excel sheet. Once the output parameters were obtained, these were validated with the results from the work of Srividhya *et al.* [7]. During the validation of the computational analysis, some variables such as the wind velocity and ambient temperature were assumed.

The simulation results showed that the effective absorptivity and the insulation thickness do not affect the performance of our model. So, these values were taken as negligible.

5.2. Validation

The result of our simulation was compared with Figure 6 from the work of Srividya *et al.* [7]. The graph shows quite similarities. Since some parameters were assumed for this simulation, the results are not exactly appropriate. For this, sensitivity analysis was performed which is discussed in Section 5.3.

Table 4 shows the value of the parameters used for validating the computational model along with the units and references from which they were obtained.

Table 4. The parameters used for validating the computational model.

Parameter	Value	Unit	Reference
α_b	0.95	-	Voinea *et al.* [13]
α_g	0.05	-	Johnson *et al.* [20]
L_i	4	mm	Ghoneyem *et al.* [17]
K_i	20.7	W/m K	[21]
R_g	0.05	-	Johnson *et al.* [20]
σ	5.67×10^{-8}	W/m^2K^4	Johnson *et al.* [20]

Table 5 shows the comparison between the output temperature or the final temperature of the absorber plate of this study with the experimental results of Srividhya *et al.* [7]. It can be seen that the difference between the two sets of data is higher for lower ambient temperatures and lower for higher temperatures, that is, around noon time.

Table 5. The comparison of the present study with the experimental results of Srividhya *et al*. [7].

Time of the day	Ambient temp. (ºC)	I(t) (W/m^2)	Output temp. (Srividhya *et al.* [7])	Output temp. (present study)
09 00	29	335	30	48
10 00	30	450	39	55.6
11 00	31	530	44	60
12 00	32	522	48	61
13 00	33	509	55	61.8
14 00	34	464	59	60
15 00	35	381	64	56

Figure 5 shows this validation result graphically, comparing the results of this present study with the experimental results from Srividhya *et al.* [7].

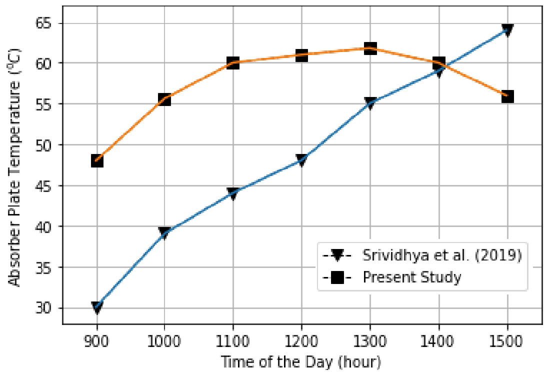

Figure 5 The comparison of the present study with the experimental results of Srividhya *et al.* [7].

5.3. Sensitivity Analysis

Sensitivity analysis is the study where some of the input variables are increased and decreased to see how significant the change in output, in this case, the final temperature of the absorber plate, is.

The following analysis was carried out in MS Excel for the given atmospheric conditions:

Solar insolation, I(t) = 500 W/m^2

Ambient temperature = 25 ºC

Wind velocity = 2.2m/s

Table 6 shows that the final plate temperature is not affected significantly by the absorber plate thickness. However, it was suggested by Ghoneyem *et al.* [17] that 4 mm is a well-balanced value for the thickness of the plate. Moreover, thicker plates will increase the manufacturing cost which is not desirable for this study.

Table 6. The variations in temperature of the absorber plate with the changes in plate thickness.

Plate thickness (m)	The final temperature of the plate (ºC)
0.001	53.57
0.004	53.59
0.008	53.6
0.01	53.6
0.02	53.64

Figure 6 below is a graphical representation of this variation. From equation (10) it is evident that increases in plate thickness L_i will increase h_b which in turn increases T_{bf} in equation (13).

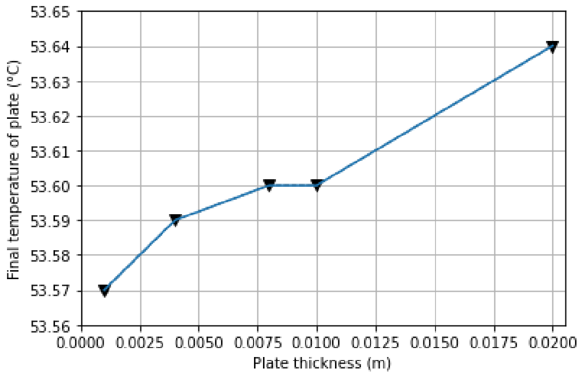

Figure 6 The variations in temperature of the absorber plate with the changes in plate thickness.

Table 7 shows that the final plate temperature decreases with increasing wind velocity. This is because stronger winds draw the warm air or heat away from the surface of the plate more than weaker winds. So, heat from the Sun will not be able to accumulate for a long time in the plate's area. Therefore, a low wind velocity is desired. This effect is also evident from the formulae in section 2.5.

Table 7. The variations in temperature of the absorber plate with the changes in wind velocity.

Wind velocity (m/s)	The final temperature of the plate (ºC)
0.5	65.67
1.0	65.1
2.2	53.59
3.0	45.5
4.4	43.92

An increase in wind velocity, v_w, results in an increase in h_{Tba} in equation (9) which in turn decreases h_b in equation (10). This relationship is graphically shown in Figure 7.

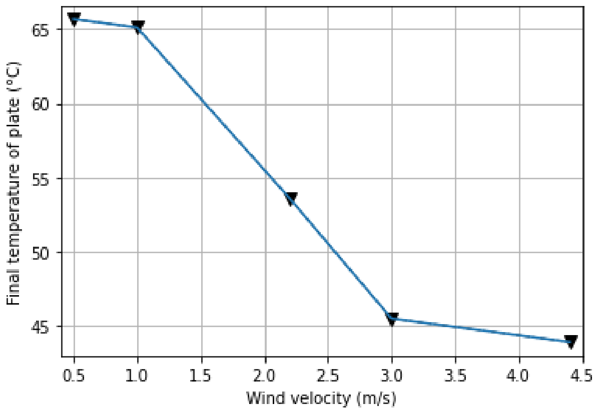

Figure 7 The variations in temperature of the absorber plate with the changes in wind velocity.

Table 8 shows that the final plate temperature increases with the increase in absorptivity of the absorber plate. This is because, according to equation (13), the absorptivity (α) of the coating material is directly proportional to the final temperature of the plate, T_{bf}.

Table 8. The variations in temperature of the absorber plate with the changes in absorptivity of the plate.

Absorptivity of the plate	The final temperature of the plate (ºC)
0.1	29.01
0.5	41.3
0.75	49.26
0.95	53.59
1	56.99

This relationship is shown graphically below in Figure 8. The variation is linear for most of the graph.

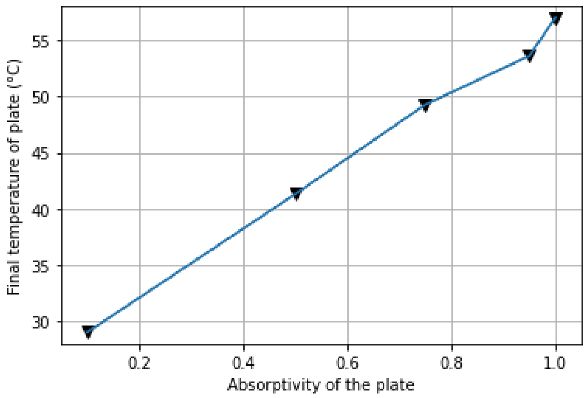

Figure 8 The variations in temperature of the absorber plate with the changes in absorptivity of the plate.

6. CONCLUSION

6.1. Concluding Remarks

In this research, the main goal was to design an efficient absorber plate for a solar air dryer. Various enhancement parameters were adopted to obtain the best performance by reaching the maximum plate temperature possible. Several coating materials were studied along with their optical and thermal properties. It was observed that most coating materials were either expensive to purchase or required an expensive technique to embed it on the absorber plate. Nickel oxide nanoparticles, having a high surface area, were chosen as the prime candidate for this study since they showed satisfactory results and its embedding process was inexpensive as well.

Following the Dunkle model [14], simulations were run and validated with similar work. After the validation of this work, sensitivity analysis of some of the input parameters was also carried out to make sure the differences in output variables of this present study and previous research are within the acceptable limit. Once the absorber plate is optimized, it would be tested with an appropriate solar dryer.

However, due to the ongoing global pandemic, the fabrication process could not be carried out and so the performance analysis was done solely by running simulations on computer software {MS Excel, CodePro). These simulation results were validated with the work of Srividhya *et al.* [7] and it showed a positive correlation. During the simulations, some parameters were assumed since some of the data required to simulate and validate were not provided in the work of Srividhya *et al.* [7].

6.2. Future Works

If the current state of the COVID-19 pandemic in Bangladesh improves, fabrication of the working model will be carried out. After that, the comparison and validation will again be performed between the working model and the simulation results of this present study. Uncertainty analysis, with the help of the Chi-test method, is also in the plans to be performed once the fabrication is made possible and it will give an idea of the degree of correctness and accuracy of the working model.

Nomenclature

α_b absorptivity of NiO coated plate
α_g absorptivity of glass
ε_{eff} effective emissivity between glass and air
h_a convective heat transfer coefficient between plate - and air mass (W/m^2K)
$I(t)$ solar insolation (W/m^2)
L_i plate thickness (mm)
K_i thermal conductivity of NiO nanoparticles (W/mK)
Pa_o partial pressure of outside air (Pa)
Pa_i partial pressure of internal air (Pa)
R_g reflectivity of the glass cover
σ Stefan Boltzmann's constant (W/m^2K^4)
T_{bi} absorber plate initial temperature (°C)
T_{bf} absorber plate final temperature (°C)
T_{amb} ambient temperature (°C)
Ta_i internal air temperature (°C)
Ta_o outside air temperature (°C)
Tg_i internal surface temperature of glass (°C)
Tg_o outside surface temperature of glass (°C)
v_w wind velocity (m/s)

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