



Experimental Study to Improve the Performance of Double Pass Solar Air Heater by Using Nanomaterials

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ABSTRACT

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Solar energy is utilized to heat air, subsequently employed for greenhouse heating and crop desiccation. The performance of SAHs, standing for solar air heaters, can be enhanced using different designs of an aluminum absorber plate. This type of SAH has been examined and contrasted with a traditional flat black-coated absorber plate, as well as with copper oxide (CuO) at concentrations of 3% and 5%. It can be utilized in continuing endeavors to improve thermal efficiency and convective heat transfer. This study's analysis relies on data from experiments examining the solar air heater technology featuring a double-pass configuration under two conditions: the conventional state and the nanomaterial-enhanced state, with varying rates of air mass flow of 0.05, 0.035, and 0.025 kg/s. The outcomes of experiments indicate that using nanomaterials with 3% copper oxide (CuO) is the best case, as it yielded, at a rate of mass flow of 0.035 kg/s, the highest outlet temperature of 42.8°C. Moreover, the conventional case's thermal efficiency ranges between 22.1% and 53.2%, while it ranges between 27.6% and 60.1% at 3% CuO and between 25.6% and 57.7% at 5% CuO. The efficiency increased by 6.9% in the 3% CuO case compared to the conventional case.

1. INTRODUCTION

Solar air heaters use natural or forced convection to transform solar energy into heat. Their performance is determined by the absorber plate coating, which is enhanced with nanomaterial-infused black paint. The heating process consists of transferring heat from the source and the transfer of moisture mass to the surrounding air [1].

Abdelkader et al. [2] created a CNTs-CuO nanoparticle coating in black paint for solar air heaters, increasing temperature differential by 22% and thermal efficiency by 24.4%. The coating improves exergy efficiency, making it an economical upgrade for drying and heating applications.

In 2023, Arani et al. [3] added fins and 20% SiO₂ nanoparticles in black paint to improve tubular solar stills, increasing the water's and the basin's temperatures by 10.88% and 10.49%, respectively. Fins increased water output by 55.18%, bringing production costs down to \$0.012/litre.

Abdulla et al. [4] looked at how three absorber plate forms (flat, corrugated, and V-corrugated) impact solar air heaters' double-pass performance. The outcomes demonstrate that the U-corrugated plate has the maximum efficiency, with 73.9% at 1.5 m/s and 69.2% at 3 m/s, emphasizing the importance of plate form in thermal efficiency maximization.

In 2014, Céspedes et al. [5] forced convection was used to generate stable turbulent flow in triangular ducts that are equilateral and horizontal, and the drop in pressure and thermal performance were examined. Constant wall heating and exterior surface insulation resulted in better heat transfer.

Dharmaraj et al. [6] reported that a graphene-based nanopaint coating on a solar air heater increased energy gain by 12.9%, raised thermal efficiency by 13.24%, and reduced heat loss by 8.48%, yielding substantial performance improvements. El Nady et al. [7] studied solar air heaters during the previous several years. Coating absorber plates with materials that increase the heat transfer rate and performance is the focus of the current investigation.

El-Sebaei and Al-Snani [8] revealed that Ni-Sn selective coatings boosted thermal efficiency by 29.23% when compared to black paint, lowering heat losses and increasing usable energy. These heaters are ideal for high-temperature applications such as agricultural drying and industrial procedures above 80°C. Mohammed Hameed et al. [9] demonstrated that employing steel wool as a porous medium in solar air heaters increases thermal efficiency by 10%, raises exhaust temperature by up to 21.32%, and improves mass flow rates when compared to typical flat plates. Jeong et al. [10] focused on the absorber surface's nanomaterial coating. Investigated the potential of coating solar absorbers with CuO nanoparticles. TiO₂-coated black paint improved solar still performance and increased temperature by 1.5°C [11]. As a blackbody absorber panel, Kabeel et al. [12] proposed using single-wall carbon nanotubes. In nanomaterials, it has a high emissivity ranging from 0.98 to 0.99.

Kumar et al. [13] in 2020 added 1% graphene to black paint on a triangle solar air heater, increasing thermal efficiency by 4.9%, to 48.23%. Graphene improves heat absorption, making it an appealing option for solar air heaters. In the study of

Kabeel et al. [14], a conventional basin and a black-painted absorber plate that contains 10-40% CuO nanoparticles were used for the experiments. Distillate weight percentages increased by 16% and 25% in solar stills that used CuO nanoparticles as opposed to those that did not. In 2016, Kollanoor et al. [15] reported that coating a solar air heater with black paint containing 6% NiO nanoparticles achieved 91% solar absorption and 7% thermal emittance.

Kumar et al. [16] applied a 1% graphene/cerium oxide-black paint covering to a roughened absorber increased exergy efficiency by 0.54% and thermal efficiency by 3.36% in solar air heaters, while decreasing entropy. Kumar et al. [17] discovered that a 0.2% graphene-black paint coating on a triangle solar air heater increased exergy efficiency by 2.47% and thermal efficiency by 4.91% while decreasing entropy generation. Kumar and Verma [18] found that covering a solar air heater with 0.3% graphene/CuO nanoparticles increases exergy efficiency by 0.169% and thermal efficiency by 3.58% while reducing entropy generation. Kumar et al. [19], coated with graphene, CuO, or CeO₂ nanoparticles to advance heat transfer and thermal efficiency. Thermal efficiency is increased by 3.58% with the graphene/CuO-black paint while decreasing entropy formation, indicating improved performance. Khanlari et al. [20] revealed that optimal thermal and exergy performance was achieved by the system utilizing perforated baffles, with thermal efficiency ranging from 58.10% to 76.22% for the nano-enhanced system and 54.96% to 72.05% for the normal system. The nano-coating boosted the exergy efficiency from 9.25% to 10.58%.

In 2023, Katekar et al. [21] added 30% aluminum oxide nanoparticles in black paint has the greatest radiative heat transfer (15 W) and temperature of the absorber plate (55.3°C), making it the most effective coating for solar thermal applications. Liu et al. [22] aimed to improve thermal performance by covering the absorber plate with various materials experimentally. Ni-Sn was shown to be the most effective coating material in this study. A 29.23% improvement in thermal daily efficiency was achieved after using a coating substance.

According to Leung et al. [23], coating absorber plates with graphene nanomaterials prevented corrosion. In addition, the absorber plate's new selective paint shows exceptional solar selectivity.

In 2021, Rashid et al. [24] looked at the thermal efficiency of fuel rod assemblies in a PWR that uses MgO-CMC nanofluid as a coolant. The results demonstrate that introducing nanoparticles enhances heat transfer, with the highest results at 4% volume fraction. The triangular array has superior heat transfer and temperature distribution compared to the square array. MgO-CMC works better than Al₂O₃ nanofluid, decreasing coolant temperature by up to 2%.

Rasachak et al. [25] in 2022 improved solar still distillate production by adding Tin Oxide (SnO₂) to the layer of black paint on the absorber plate, whose temperature rose with larger SnO₂ concentrations, peaking at 101.61°C indoors and 74.96°C outdoors. SnO₂ increases solar radiation absorption in the ultraviolet and near-infrared spectrums, boosting the system's thermal performance. Šest et al. [26] added ~0.05% graphene nanoplatelets to solar absorber coatings improved corrosion resistance without altering optics, providing a cost-effective solution for extending longevity in severe conditions.

Moorthy et al. [27] investigated the effect of graphene nano coatings on the thermal efficiency of a solar air heater (SAH), comparing systems with internal baffles and those without.

Nine different coating configurations were tested. Case 9, using 2 wt% graphene in both acrylic and black paint, showed the best results, achieving thermal efficiency of 83.8%, a 700.4 W useful heat gain, and a 1.97 thermo-hydraulic performance factor. The findings confirm that higher graphene content and the use of baffles significantly improve SAH performance.

By applying activated carbon derived from leftover tea dust to the absorber, Sathyamurthy et al. [28] improved a double pass solar air collector (SAC). Compared to conventional black paint, the new coating significantly improves thermal and exergy efficiency. At a flow rate of 1.8 kg/min, exergy efficiency 6.2% (vs. 3%) and thermal performance reaches 96.2% (vs. 77.8%). The results show the potential of converting agricultural waste into efficient solar absorber materials.

Venkatesh et al. [29] enhanced a double-pass solar dryer using a hybrid CuO-Fe₃O₄ nano-coating. The coated system shows better thermal and drying performance than the uncoated ones. Peak air temperature reached 66.5°C, average thermal efficiency was 69.7%, and red chilies had the best drying rate (0.81 kg/h) and exergy efficiency (8.4%). The hybrid coating improves solar energy absorption and drying efficiency for agricultural products.

In this research, the effect of CuO nanomaterial on an aluminum absorbent plate with black coating at different ratios of 3%, 5% will be investigated and compared with a conventional absorbent plate.

2. EXPERIMENTAL SET-UP

2.1 Experimental rig

A solar air heater's (SAH) thermal performance was examined in two cases through the experimentation carried out in this study. In one case, the absorber plate is conventional, and in the other, it contains copper oxide nanomaterial in varying amounts (3%, 5%). The SAH and measuring devices are the main part of the experimental setup. The experiments were conducted in Babylon, Iraq, experiencing winter throughout December, January, February, and March in 2024-2025. Iraq's geographical coordinates are approximately 32.48389° latitude and 44.4311° longitude. Iraq's strategic location in the northern hemisphere makes it ideal for utilizing abundant solar energy. The inclination of this heater was designed to be appropriate for the nearby latitude. The DPSAH slope has been adjusted to 47° south. In a cool environment from 8:30 a.m. to 2 p.m., practical tests were conducted. The solar-transparent surface, made of glass, measured 2000 × 1000 mm and was 5 mm thick. The standard absorber plate utilized in this research had dimensions of 2000 × 1000 mm and a thickness of 0.5 mm, whereas the absorbent plate was composed of aluminum and coated in a dark black. Figure 1 shows the double-pass solar air heater in full detail, including the thermocouple, fan, glass, and base of the device (Table 1).

Two different concentrations of copper oxide (CuO) nanoparticles (3% and 5%) were combined with black coating, each in a 1-kilogram batch. The mixes were then applied as a coating to three aluminum plates. The mixture was mechanically mixed at the University of Babylon for half an hour, taking all necessary precautions against nanoparticles. It was then incubated in an ultrasonic device for three hours, as shown in Figure 2.



Figure 1. Displays the experimental set-up

Table 1. Characteristics of the solar air heater

Items	Characteristics	
	A	B
1	Type of flow	Double-pass
2	Solar air heater box	2000 mm × 1000 mm × 150 mm
3	Insulator	20 mm wood
4	Absorber	Aluminium, 2000 × 1000 × 0.5 mm
5	Glass	5 mm tempered glass, normally ironed, 95% transmittance, 95% Absorptivity
6	Coated absorber	28% Emissivity, 95% Absorptivity
7	Fan	Cross-flow fan (220V, 1.0A)



Figure 3. Ultrasonic device

Table 2. Copper nanoparticles and nano powder CuO properties

Sample	Characteristics	
	A	B
1	Purity	99%
2	APS	<100nm
3	SSA	>20m ² /g
4	Morphology	spherical
5	Bulk Density	0.79 g/cm ³
6	True Density	6.4 g/m ³
7	Color	Black brown

Table 3. Properties of the nanomaterial after mixing them with black paint

Sample		Density ρ	Thermal Conductivity K
1	Black paint without nano	0.9730	0.156
2	Black paint with CuO 3%	1.0149	0.152
3	CuO 5%	1.0273	0.147

2.2 Experimental procedure

- (1) Recording Intervals: Parameters were recorded every 30 minutes.
- (2) Airflow System: A 200 mm × 200 mm blower was used to drive air through the SAH.
- (3) Ventilation & Heat Transfer: The fan ensures optimal heat transfer and ventilation within the SAHD.
- (4) Temperature Measurement: Measured at air inlet, air outlet, and absorber plate.
- (5) Thermocouples are placed at various positions along the SAH.
- (6) Airflow Control: A voltage regulator controls fan speed.
- (7) Allows researchers to adjust airflow rates.
- (8) Rates of Mass Flow: Evaluated at 0.05, 0.035, and 0.025 kg/s.
- (9) A solar power meter analyzes incoming solar energy.
- (10) A temperature data logger records thermocouple readings and other relevant data.
- (11) Standard case: Black paint without nanomaterials.
- (12) Comparison: Two cases of black paint mixed with copper oxide.



Figure 2. Mixture of black paint with CuO nanomaterial

The incorporation of copper oxide (CuO) nanoparticles into a black coating in a solar air heater improves the transfer of heat as well as the process by which the air in the system absorbs solar radiation. CuO nanoparticles have excellent thermal conductivity and solar radiation absorption capabilities, which improve the performance of traditional black coatings. When combined with the coating, these nanoparticles promote uniform heat distribution throughout the aluminum surface, lowering thermal losses while enhancing air heating efficiency and speed. This enhancement improves the solar air heater's overall performance, allowing it to convert solar energy more effectively into useful heat. Figure 3 shows the mixture of copper oxide and black paint nanomaterial after mixing it in the ultrasonic device. Table 2 shows the properties of copper nanoparticles and CuO nano powder. Table 3 illustrates the properties of the nanomaterials after mixing them with black paint.

Figure 4 shows the equipment used to improve the efficiency of the double-pass solar heater and also the parts of the device.



Figure 4. Experiments on double-pass solar air heater

3. RESULTS AND DISCUSSION

Nanostructured copper oxide (CuO) is utilized in solar air heaters to develop thermal conversion efficiency and solar energy absorption because of its excellent thermal conductivity and chemical stability. Integrating CuO nanoparticles into the absorber coating or heat exchanger enhances heat transfer, resulting in greater air temperatures and overall system performance. This advanced nanomaterial technology optimizes solar thermal applications, resulting in an efficient and sustainable solution for renewable energy systems.

Environmental factors like the volume of sunlight reaching the device and the ambient temperature have a substantial influence on the SAH's efficiency, which stands for Solar Air Heater. The experimental tests started at 8:30 AM and lasted until 2:00 PM. The ambient temperature ranged from 8.1 °C in the morning to approximately 26.3 °C at 2:00 PM.

Solar radiation intensity has a main influence on the amount of energy that the solar collector has the ability to capture. The solar irradiance was approximately 480 W/m² at 8:30 AM, increased to 960 W/m² at 12:00 PM, and later decreased to 721.4 W/m² at 2:00 PM. The experimental sessions extended until 2:00 PM.

The variation in outlet temperature profiles increased with rising solar radiation. Additionally, it peaked during the height of solar radiation. The largest temperature possible at the outlet in the flat SAHd reached 41 °C at a 0.025 kg/s mass flow rate, while the highest outlet temperature in CUO was achieved at a 3% ratio for a rate of mass flow of 0.035 kg/s. The outlet's temperature profiles followed the same trend observed in the rate of mass flow variations, indicating an upsurge in outlet temperature with rising solar radiation, reaching its highest quantity when the intensity of solar energy was at its peak. Additionally, in the afternoon period, the temperature profiles declined because of the reduction in solar radiation.

Figures 5, 6, and 7 show the temperature difference during the time from 8:30 a.m. to 2:00 p.m. in three cases (the conventional case, when adding 3% copper oxide and 5% copper oxide), at speeds (2.5, 3.5, and 5 m/s) and at mass flow rates (0.025, 0.035, and 0.05 kg/s). The best temperature difference was at CuO 3% at speed 2.5 m/s, where the greatest temperature differential, recorded at 12:30 p.m., was 23 °C.

Figures 8, 9, and 10 show the efficiency percentage during the day from 8:30 am to 2 pm in three cases (the traditional case, 3%, and 5% copper oxide), where each figure represents a specific speed (2.5, 3.5, and 5 m/sec), and the best efficiency was with 3% copper oxide. The efficiency reached 60% at the speed of 5 m/sec and at the time (9 and 10 am), with almost the same estimate.

The calculations were conducted by considering the duct as a system governed by the equation that follows [30]:

$$Q = \dot{m}C_p(T_o - T_i) \quad (1)$$

$$\dot{m} = \rho VA \quad (2)$$

where, $\dot{m}$ denotes the rate of mass flow (kg/s), C_p denotes the specific heat of the air (kJ/kg.°C), T_o denotes the outlet air temperature (°C), T_i denotes the inlet air temperature (°C), ρ denotes the density of the fluid (kg/m³), A denotes the cross-sectional area through which the fluid is flowing (m²), and V denotes the velocity of the fluid (m/s).

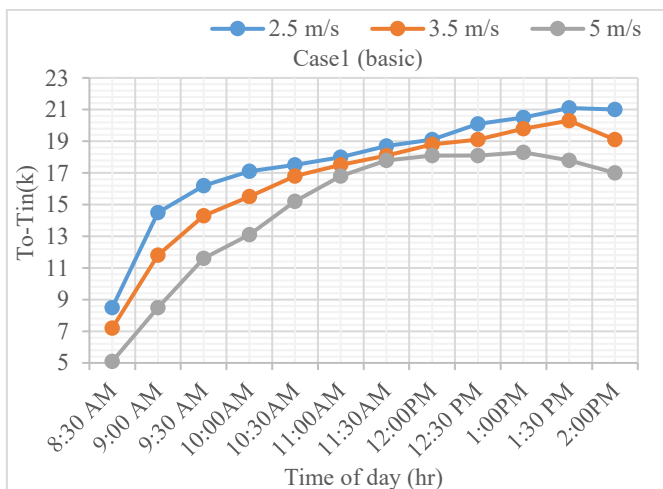


Figure 5. Variation of temperature different with the solar time for the conventional case with mass flow rates (0.025, 0.035, and 0.05)

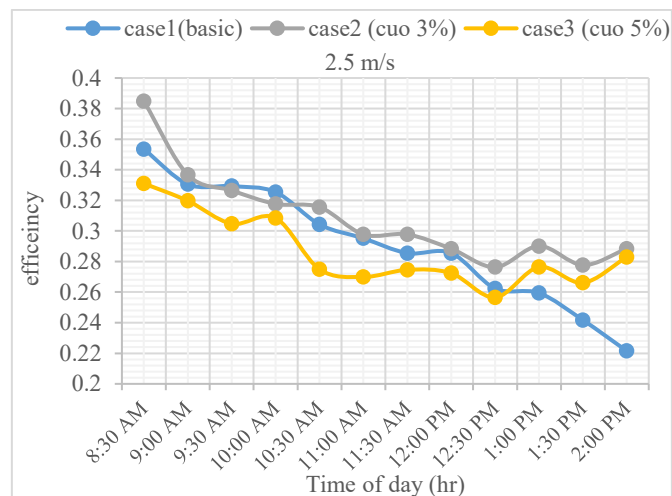


Figure 8. Efficiency percentage for every half hour of the day at a speed of 2.5 m/s for the three cases: the conventional case, and with 3% and 5% copper oxide

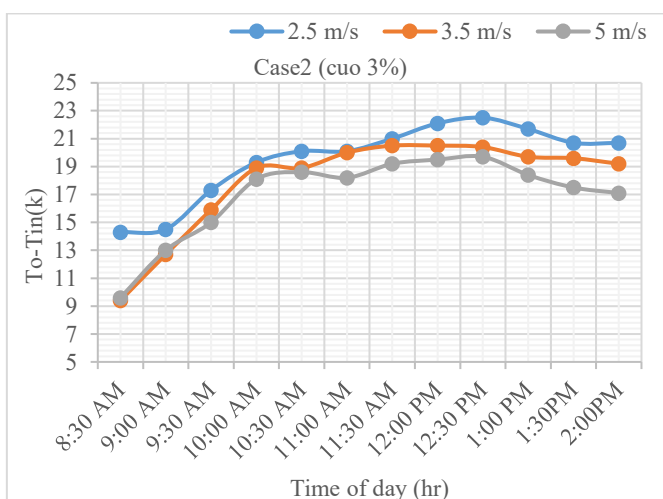


Figure 6. Variation of temperature different with the solar time for the CuO 3% and mass flow rates (0.025, 0.035 and 0.05)

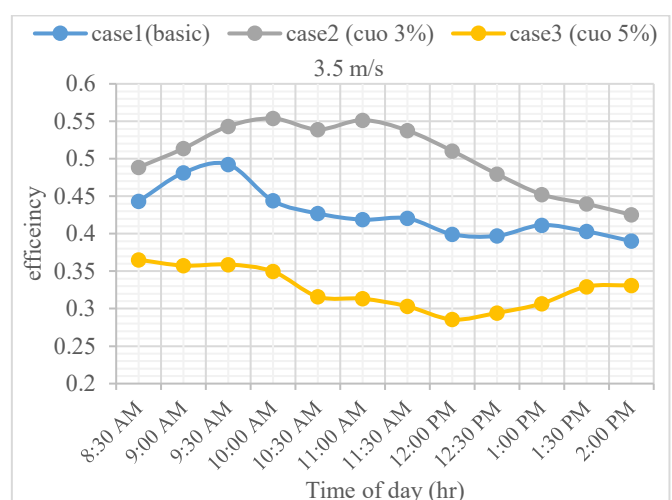


Figure 9. Efficiency percentage for every half hour of the day at a speed of 3.5 m/s for the three cases: the conventional case, and with 3% and 5% copper oxide

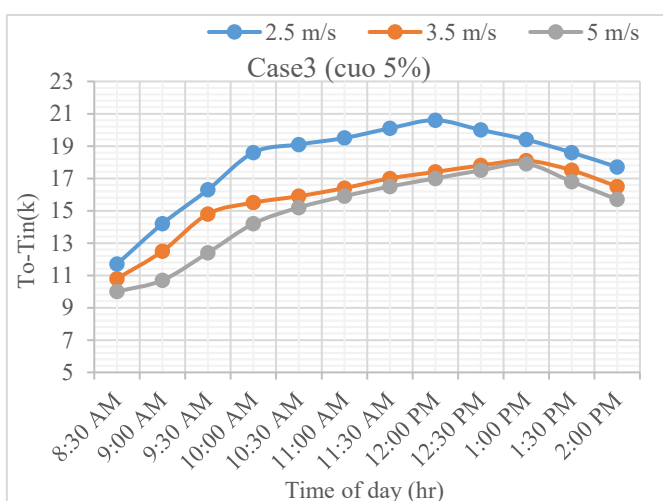


Figure 7. Variation of temperature different with the solar time for the CuO 5% and mass flow rates (0.025, 0.035, and 0.05)

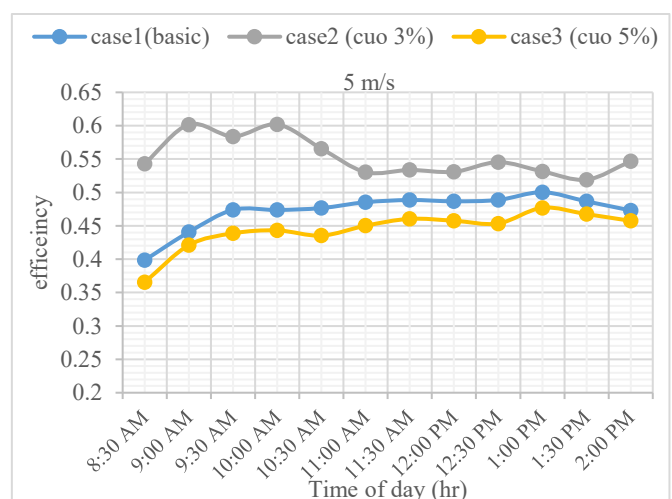


Figure 10. Efficiency percentage for every half hour of the day at a speed of 5 m/s for the three cases: The conventional case, and with 3% and 5% copper oxide

The efficiency of the SAH may be determined using the equation that follows [31, 32]:

$$\eta_i = Qu / Ac \cdot I \quad (3)$$

where, Ac denotes the collector area (m^2), I denotes solar radiation (W/m^2).

4. CONCLUSIONS

According to the experimental study, coating the absorber plate of a double-pass solar air heater with copper oxide (CUO) nanoparticles can significantly increase thermal efficiency compared to a conventional design. The design, with a 3% CUO concentration and a mass flow rate of 0.035 kg/s, achieved the best performance under all tested temperature conditions. The highest thermal efficiency was achieved at a mass flow rate of 0.05 kg/s, suggesting it may be a practical option for mid-latitude winter regions where efficient heat capture is essential. Both commercial and residential heating applications could benefit from this enhanced design's ability to lower energy consumption and encourage the use of renewable energy sources.

Future studies should investigate nanomaterial concentrations suitable for different climate zones, advanced coating techniques to improve nanoparticle stability and heat transfer properties, and long-term field tests to confirm cost-effectiveness and durability in real-world environments, thereby increasing system efficiency and operational life.

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