INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 14-05-2020

Accepted: 19-05-2020

Published: 14-06-2020

Editor: Dr. Natarajan Gajendran

Citation: Mehta P, Kumar S, Patel V, Joshi A (2020) Mathematical modeling and performance assessment of solar air collector. Indian Journal of Science and Technology 13(18): 1803-1810. https://doi.org/10.17485/IJST/v13i18.608

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

Mathematical modeling and performance assessment of solar air collector

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Abstract

Background: The use of solar air heater in drying has been increasing in recent years, because of their simplicity and economic configuration. **Methods:** Design and testing of the corrugated solar collector have been carried out in the present study. The overall system was designed and tested at Gujarat Power Engineering and Research Institute, Mehsana, India (GPERI, 23°31'37.4"N72°23'14.1"E). Exergetic efficiency, thermal efficiency, and temperature outlet at the same mass flow rate and solar irradiance were the major parameters for the present study. The designed system was tested by varying the mass flow rate of 0.1075, 0.215, and 0.3225 m^3/sec. **Findings:** It was found that the temperature of the corrugated collector was maximum at 92°C at solar radiation of 750 W/m^2. Whereas thermal efficiency was found to be 65.10% the same radiation. It was depicted from the tests that the corrugated plate performs more efficiently than a flat plate collector due to surface roughness. **Applications:** It is a good practice in a region where solar radiation is higher all year to implement this type of arrangement for the utilization of any solar gadget, and to enhance its performance efficiency. **Novelty:** it can be observed that collector outlet temperature in the semi-arid region of Gujarat was maximum at the minimum collector area. This should be the best design and thermal performance in a semi-arid climate.

Keywords: Solar air heater; Drying; Collector outlet temperature; Exergy analysis

1 Introduction

With the rapid rise in the population and the living standards, the world seems to engulf into a major crisis, called energy crisis. If this population growth continues at the same pace the condition would go from bad to worse. The reserves of conventional sources of energy like coal, petroleum, and natural gas are depleting at a very fast rate to fulfill the demand of the growing population [1,2].

The use of solar air heater has been increasing in recent years, because of their simplicity, cheapness, ease of their maintenance and operation, friendly to the environment, and non-fuel operation. Such heaters are implemented in many applications that require low to moderate temperatures below 60°C[3].

In the agricultural area, the main application of the solar air heater is drying, utilizing solar drying. Using a solar dryer, the drying time can be shortened by about 65% compared to natural sun drying because, inside the dryer, it is warmer than outside; the quality of the dried products can be improved in terms of hygiene, cleanliness, safe moisture content, color and taste; the product is also completely protected from rain, dust, insects, rodents; and its payback period ranges from 2 to 4 years depending on the rate of utilization[4]. The quality of the dried product is mostly dependent on drying air temperature, velocity, and drying time[5,6]. On the other hand, the thermal efficiency of the solar air heater is poor due to the low heat transfer capacity and low heat conductivity of air. Therefore, several researchers have studied and designed several types of solar air heaters to improve their performance[7–12].

The performance of two components of a solar drying unit (collector and storage system) was investigated without drying energy supplement. They used a V-corrugated absorber and single glazing in the air collector and metal parallelepiped system for the storage unit. According to their experimental results, average collector efficiency and outlet temperature were found as 30.52% and 54.06°C, respectively[13].

Experimental results of a new-design plate collector used to heat air in new desalination humidification– dehumidification process has been presented. Also, the effects of different parameters on the collector efficiency, such as solar radiation, wind velocity, ambient temperature, air mass flow rate, air temperature, and humidity through the collector were investigated[14]. The maximum temperature of the V-grooved collector was observed to be 390K at the less mass flow rate, by increasing mass flow rate it was observed to be decreasing[15].

The effect of the airflow line on the performance of solar collectors with absorber slices have four different surface geometries. The efficiency of collectors increases depending on the collector surface geometry and extension of the airflow line. As a result, it appears that if the surface roughness is increased, the heat transfer and pressure loss increases[16]. The efficiency of a solar collector becomes higher with different geometry types having roughness elements on the absorber plate. In this study, the relative roughness height is considered a strong parameter for the effective efficiency of a solar collector[17]. Performance of solar air heater with 60° V-down discrete rectangular cross-section repeated rib roughness on the airflow side of the absorber plate was analyzed. The effects of the various ambient, operation and design parameters on the thermal and effective efficiency of air heaters have been investigated. The study shows that at air mass flow rates less than about 0.04 kg /s m^2 of the absorber plate, roughened duct solar air heaters provide a significant performance advantage over the smooth ducted solar air heater. At the mass flow rate of about 0.045 kg/s m^2, the effective efficiency of the roughened and smooth duct solar air heaters are practically the same[18].

This paper presents a comparison of air outlet temperature, absorber plate temperature, and thermal efficiency of solar air heaters having flat and corrugated plates and for 0.1075, 0.215, and 0.3225 m^3/sec air flow rates. A mathematical model was proposed and collector outlet temperature was calculated by several researchers[19,20], but in the present study, the authors calculate the value of collector outlet temperature at each definite discrete node over the entire plate which can be novel study. Also, an analysis was conducted in a semi-arid region where it can be practically implemented for the utilization of community for developing such solar collector assisted gadgets such as solar dryer, solar still, and many more.

2 Design and procedure for the experiment

2.1 Design procedure

As of the collector, the area is the function of solar radiation, inlet air temperature, it was determined on this basis. An absorber plate was made up of stainless steel material with black chrome as a coating material to absorb more solar radiation. It was fabricated locally with economically viable materials. The plate was made with dimensions of 750 mm × 500mm × 182 mm respectively. The schematic diagram of the designed system is depicted in Figure 1. Roughness on the absorber plate was provided uniformly with toughened glass provided over it. Table 1 presents detailed design data for the designed collector.

2.2 Experimental procedure

Proper care was exercised while installing and operating a solar collector. It was ensured to be well insulated before performing experiments. Figure 2 shows experimental set up of corrugated plate solar air heater. The orientation of the designed set-up was at 23°, nearly latitude of the location. All the measuring instruments were checked for uncertainty and error, prior experimentation. Thermal losses of cover due to convection as well as radiation process are assumed as constant.

Here, Thermocouples were positioned properly. Inlet as well as outlet temperatures were measured with help of K Type

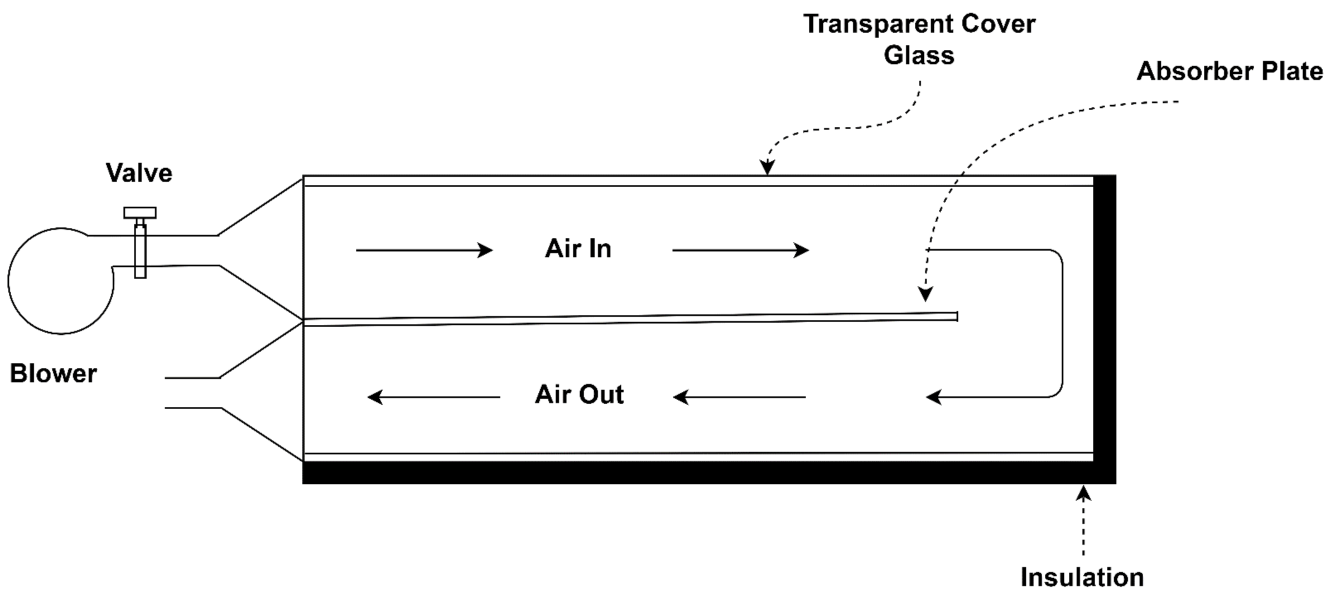

Fig 1. Schematic diagram of designed system

Table 1. Design configuration of solar collector

Absorber material	Aluminum
Plate thickness	0.002 m
Absorber coating	Dull black paint
Glazing	Single glass (thickness of 0.004 m)
Agent fluid inflow ducts	Air
Width of the duct	0.9 m
Collector side wall height	0.1 m
Airflow duct height	0.043 m
Length of the collector	1.9 m
Emissivity of the glass covers	0.85
Emissivity of the absorber plate	0.95
Emissivity of the bottom plate	0.95
Tilt angle	35°
Insulation thicknesses	0.05 m
Thermal conductivity of insulation	0.043 W m^{-1} K^{-1}
Heat transfer coefficient of aluminum	210 W m^{-1} K^{-1}
Heat capacity of aluminum	0.90 KJ g^{-1} $°C^{-1}$(IN SI unit)

thermocouples. Thermocol was used as an insulating material for the designed set up and it was placed at the bottom of the plate up-to 5 mm. Ambient temperature was measured by Mercury thermocouple. Solar radiation was measured by a Pyranometer. One set of blowers was provided to regulate the mass flow rate of air. It was ensured that glass cover was clean before starting an experiment and dust-free environment inside the plate. An experiment was started at 10 A.M. and continued till 5 A.M., all the parameters were measured at the hourly interval with varying mass flow rate conditions.

3 Mathematical modeling of collector outlet temperature

The suitable design of the absorber/collector is very vital for any solar drying system as the collector efficiency plays a key role in determining the overall system efficiency. For the prediction of collector outlet temperature a methodology was developed,

Fig 2. Set-up photograph for the designed system

whereby the collector plate was partitioned into n- number of nodes. The value of plate temperature, glass temperature, and the collector air temperature was calculated at each node, which gave a prediction for the collector outlet temperature. The detailed procedure and modeled equation for calculating collector outlet temperature were presented in literature and is given by [18].

$$T_{co}(i+1] = T_{co}(i] + \frac{\triangle y}{m' C_p}\{h_{cog}\left(T_{glass}(i] - T_{co}(i]\right) + h_{cplate}\left(T_{plate}(i] - T_{co}(i]\right)\} \quad (1)$$

Collector efficiency, η_c (%), is defined as the ratio of heat collected by the drying air to the radiation incident on the absorber surface [18]. While solving the above governing equations, the collector plate was divided into ten numbers of parts, and the temperature of the air at the first part was taken equal to the ambient temperature.

4 Exergy analysis

Here exergy values were obtained from the experimentally measured values of the collector plate by employing the law of energy balance. Following general exergy equations are applied for steady-state analysis [21]:

$$E = \bar{C_p}\ [(T - T_{amb}) - T_{amb} ln\frac{T}{T_{amb}}] \quad (2)$$

For exergy calculation at the collector inlet.

$$E_{ci} = \bar{C_p}\ [(T_{ci} - T_{amb}) - T_{amb} ln\frac{T_{ci}}{T_{amb}}] \quad (3)$$

To calculate the exergy at the collector outlet

$$E_{co} = \bar{C_p}\ [(T_{co} - T_{amb}) - T_{amb} ln\frac{T_{co}}{T_{amb}}] \quad (4)$$

5 Results and Discussion

The designed absorber plate was operated under three varying mass flow rate conditions as 0.1075, 0.215, 0.3225 m^3/s. Figure 3 depicts different temperatures under three test conditions and it was found that the maximum collector outlet temperature was attained to be 92°C at 0.1075 m^3/s mass flow rate at 750 W/m^2 solar radiations. Hence, as the mass flow rate is the reduced

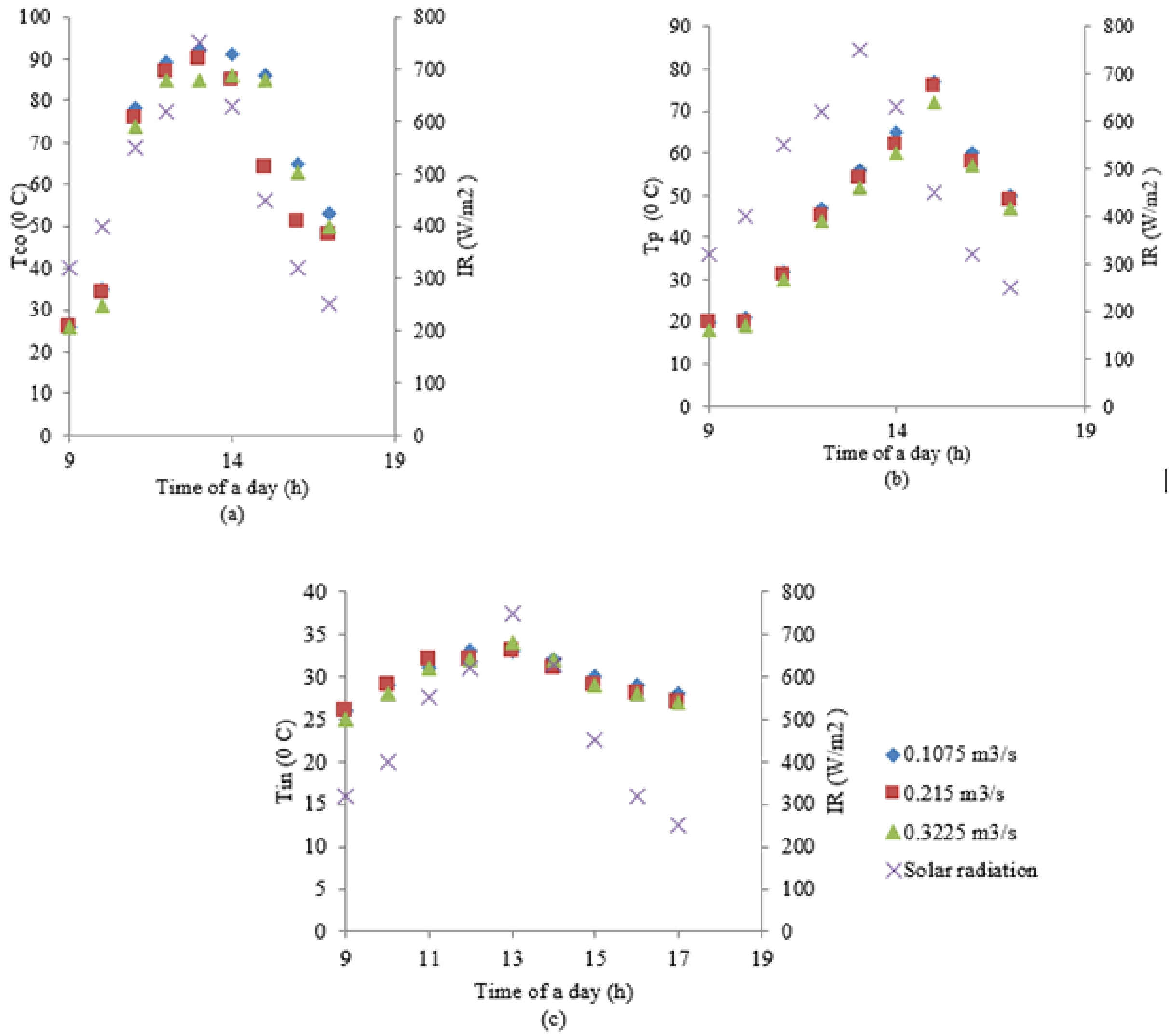

Fig 3. (a) Plot of collector outlet temperature Vs. IR Vs. time of day at different mass flow rates. (b) Plot of collector plate temperature Vs. IR Vs. time of day at different mass flow rates. (c) Plot of collector inlet temperature Vs. IR Vs. time of day at different mass flow rates

temperature at the end of the collector is achieved higher. Figure 3 (a), (b), and (c) presents collector outlet, plate, and collector inlet temperature respectively, under the same solar radiations.

Measured experimental data along with required thermal parameters were utilized to achieve the predicted collector outlet temperature using equation 1. Equations were solved using programming language SAGE math and collector outlet temperature were predicted at each step of the plate, whereas it was divided into ten number of parts. Figure 4 (a) and (b) show the results for predicted (series 2) with error bars of 5%, and measured (series 1) collector outlet temperature along with solar radiation (series 3) at each time interval. As from the plot, measured value and predicted value for the temperature is nearly the same. After 4 P.M. it was observed that measured values are more than the predicted value, the reason being said that heat absorbed by the collector was liberated during less solar radiation. Whereas Figure 5 (a) and (b) presents thermal and exergy efficiency along time of a day and plate temperature respectively. The thermal efficiency of the corrugated plate was found maximum to be 65.10% at maximum solar radiations.

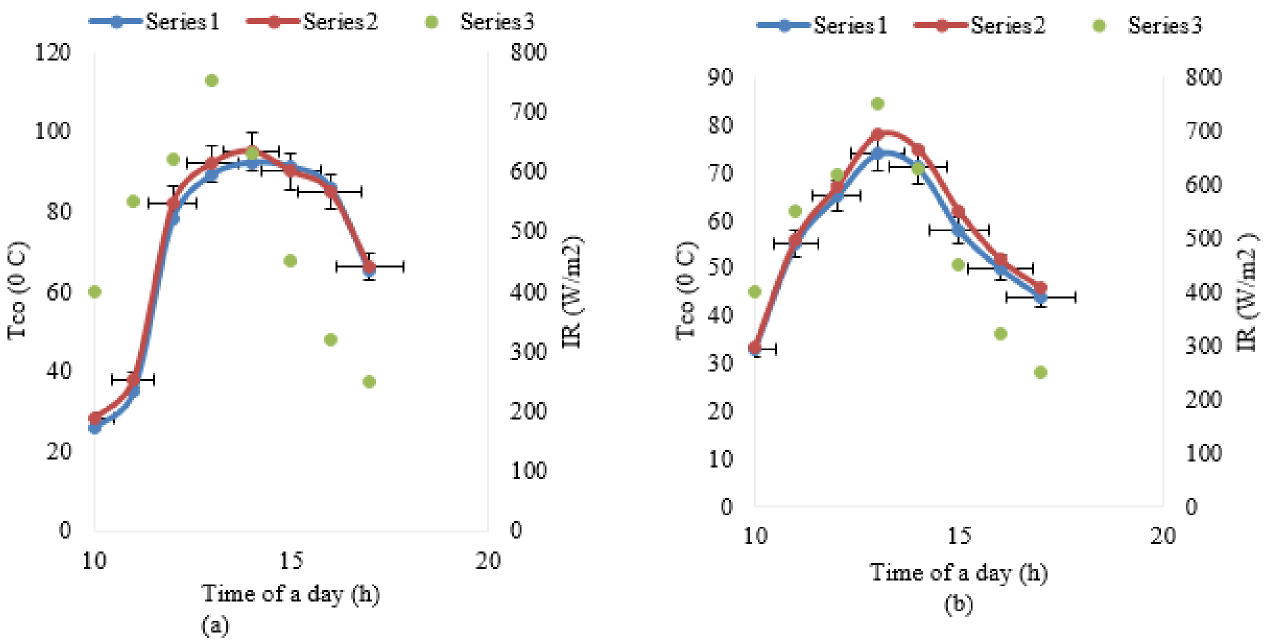

Fig 4. (a) , (b) Plot of Collector outlet temperature Vs. time of a day Vs. solar radiations

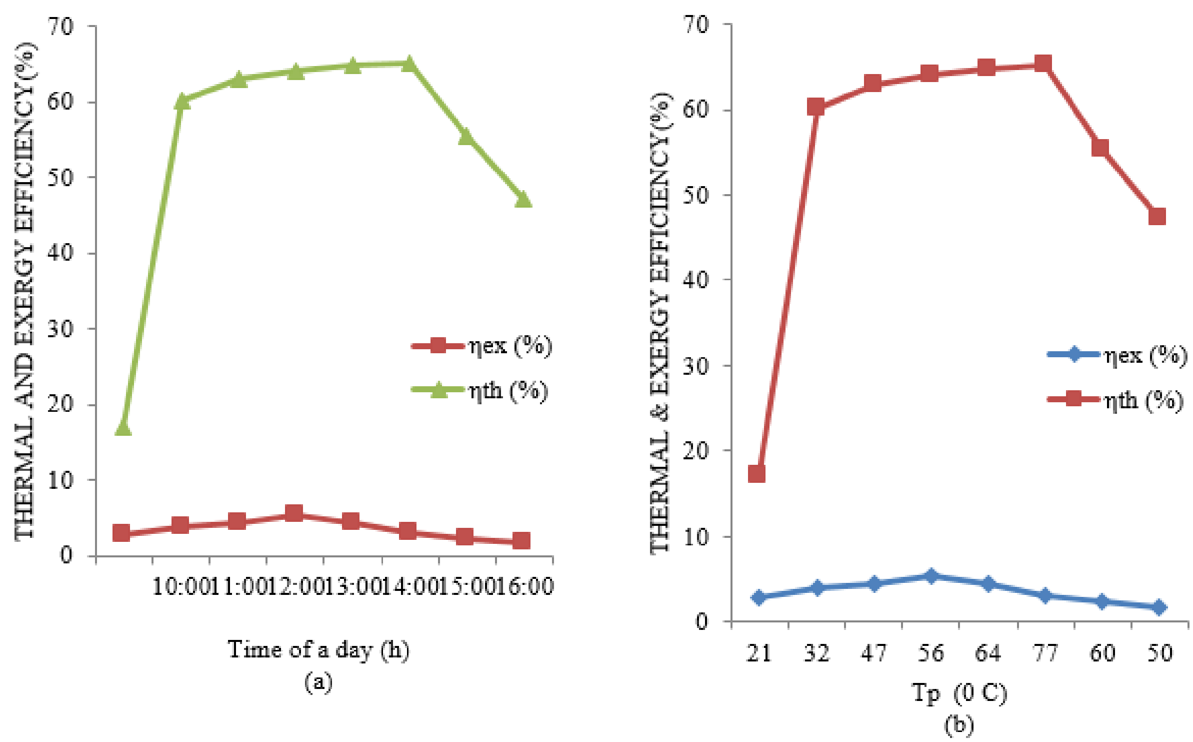

Fig 5. (a) Plot of thermal and exergy efficiency Vs. Time of a day.(b) Plot of the thermal and exergy efficiency Vs. plate temperature.

6 Conclusion

- The efficiency of the collector is very much dependent on airflow rate and as efficiency increased with flow rate, outlet temperature decreased correspondingly.
- The absorber plate temperature of the solar air heater obtained with corrugated absorber plate temperature is more than the Flat absorber plate.
- Solar air heater Absorber plate temperature increases with the increase of solar insolation when the mass flow rate remains constant.
- Thermal efficiency greatly depends on Local time and solar isolation.
- For the future investigations, it is suggested that increasing the differences of the surface and airflow areas of the absorber plates will help to compare the absorber plates in terms of efficiency and economy, more clearly.

Nomenclatures

Nomenclatures	
Cp	Specific heat of air, KJ/Kg K
E	Exergy, KJ
hcog	Heat transfer coefficient of glass, W/m2K
hcplate	Heat transfer coefficient of the plate, W/m2K
i	Number of nodes,-
m'	Mass flow rate, kg/s
Tamb	Ambient temperature, K
Tglass	Temperature of glass, K
Tco	Temperature at collector outlet, K
Ti	Inlet temperature at collector, K
Tplate	Temperature of plate, K
Δy	Distance between two consecutive nodes,-

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