A Review on Performance of Evacuated Tube Solar Collector for Various Working Parameters

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Abstract

Solar energy has been the most versatile and abundant energy source with a limitless supply of solar radiation. An evacuated solar collector nets solar energy from the sun is one of the most suitable and efficient collector types. This paper tried to answer why evacuated collector is preferred, their structure, types of evacuated collectors, applications, and issues reviewed. Many solar absorber systems in the market absorb solar thermal energy and convert it into work. But it has a limitation of working temperature. Many scientists are working to improve the working temperature of these systems. Evacuated solar collector gives promising results in this area, but it also limits lower working temperatures. In this paper, we discuss the application of solar evacuated tube collectors their working and principles. Many parameters affect the performance of the ETSC system, working fluid, coating, mass flow rate, and condenser structure. In this paper, we discuss the individual effect of that parameter and the combined effect of that parameter on the performance of ETSC. We found a significant result in a combination of the parameter. Nanotechnology has its role in improving the working temperature; we survey nanotechnology impact on performance enhancement. Based on all available literature, it can be said that an evacuated tube collector can propose a higher amount of efficiency than the other various types of collector. Few challenges have been identified which need to be wisely taken care of before installing it.

Keywords: *- Solar Evacuated Tube Heat Pipe, Working fluid, Inclination angle, Flow rate, Condenser.*

INTRODUCTION

The richest and the cleanest source of renewable energy on earth is solar energy. It is reasonable to collect solar energy efficiently, which can be further converted into a more valuable form by thermal, electrical, or chemical processes. The solar radiation is not constant, which makes it unfavourable when energy is needed at nighttimes. For such reason, the energy must be collected efficiently to use most solar radiation during the daytime. Researchers have conducted their research to explore the possibilities to maximize solar radiation collection for generating heat energy. The solar water heater is the greatest system of energy conversion. Solar thermal collectors are the most critical components of a solar heater system to collect solar radiation and converts that collected radiation into a useful form. The overall performance of a solar water heater is dependent upon the type of solar collectors used. The solar collector is designed to absorb the shorter sunlight wavelengths (0.3 – 2mm in length) but prevents heat wavelengths (2-10mm in length) from escaping (1). There are two types of solar collectors: concentrating and non-concentrating collectors. The collector area is defined as the area intercepting the incident solar radiation, and the absorber area is defined as the area that effectively absorbs the radiation. A concentrating solar collector usually has a concave reflecting surface that collects the sun's beam radiation on the indenting area and targets very small absorbers, reducing heat losses and making it suitable for high-temperature applications. In a non-concentrating solar collector, the absorber and intercepting areas that collect the sun's beam and diffuse radiation are the same, making such a system suitable for low- and middle-temperature applications. Collectors can be classified according to their indicative temperature range, which is listed below.

Very low temp = 10 ^{o}C to 25 ^{o}C
Low temp = 25 ^{o}C to 50^{o}C
Medium temp = 60 ^{o}C to 130 ^{o}C
High temp = 130 ^{o}C to 600 ^{o}C
Very high Temp = over 600 ^{o}C

A comprehensive list of solar collectors with their operating temp and efficiency is shown in Table 1.

Table 1 Types of solar collector

Motion	Collector type	Absorber type	Temperature range (C)	Efficiency (%)	category
Stationary	Flat Plate Collector (FPC)	Flat	30-80	45-60	Low Medium
	Evacuated Tube Collector (ETC)		50-200	30-50	Medium-High
	Compound Parabolic Collector (CPC)	Tubular	60-240	30-40	Medium-High
Single-axis sun tracking	Fresnel lens collector (FLC)		60-250	8-10	Medium-High
	Parabolic Through Collector (PTC)		60-300	14-16	Medium-High
	Cylindrical Trough Collector (CTC)		60-300	15-20	Medium-High
Two-axis sun tracking	Parabolic Dish Reflector (PDR)	Point	100-500	20-30	Medium-High
	Spherical Bowl Reflector (SBR)		70-700	20-30	Medium-High
	Heliostat Field Collector (HFC)		150-2000	12-18	Very High

The conventional solar water heating system could bea well-established technology but limited to domestic applications like water heating, space heating and cooling. Traditional solar flat plate collectors are inefficient in many industrial applications, requiring energy transfer at medium-high temperature conditions. The space surrounding the surface should vacuum to widen the working spectrum and reduce the thermal losses. This vacuum acts as a perfect insulator and traps solar radiation in glass tubes, and hence appreciable efficiency can be achieved. This vacuum envelope of tubular geometry is called an Evacuated Tube Solar Collector (ETC).

This paper reviews previous studies on the solar water heating system using evacuated tube collectors with different performance affecting parameters and their suitability in solar thermal systems for domestic and industrial applications—some of the recommendations of the future work for this research field.

EVACUATED TUBE COLLECTOR

Many researchers suggest that Evacuated Tube Collector has lots of advantages over flat plate collectors. Evacuated tube collector contains glass tubes made from exceptionally strong borosilicate glass, outer tube, which has lower reflectivity and higher transmissivity and absorber plate, coated with a suitable coating that increases absorption of solar energy and decreases the reflection, thereby fastening the heat in a vacuum-sealed glass tube and hence very high temperatures can be attained. The endings of tubes are merged, and a vacuum is generated between them via the evacuation process. The absorber plate will absorb solar radiation and transform it into heat—that heat transfersfrom the absorber plate through working fluid into heat pipe. The heated fluid escalates to the top of the pipe, where it heats up water that can be scattered by a heat exchanger called "manifold" in an insulated header shielded by protecting sheet metal. When heat transmits to water fluid flowing from the connecting manifold, working fluid cools down from gas to liquid, and it drops to the bottom of the heat pipe, which is to be reheated. This process goes on till solar energy is available. Evacuated tube collectors can be placed with the lowest tilt angle value of about 25° so that internal fluid in the heat pipe is coming back to the hot absorber. The incidentangle of sunlight on cylindrical tubesisat 90oC for the whole day; hence peak absorptionis continuous for an ETSC(2). Evacuated-Tubes collector contains numerous rows of glass tubes associated with amanifold to reach high temperatures. Evacuated Tube Collector is used in different industrial applications, in which high water temperatures need to be generated. The figure shows the working principle of the evacuated tube collector. The issue associated with evacuated tube collectors is that it is hard to remove heat from the absorber. Commercial Methods which are available to collect heat from evacuated tubes include:

Heat Pipe

Heat pipe with evacuated tube collectors is connected to a metal absorber coated with a suitable coating in a single vacuumed tube through a glass-to-metal seal. The heat pipe within the tube is exiled of air but comprises a small amount of a low-pressure alcohol/water liquid plus some added additives to escape from losses.

Direct Flow

Direct-flow evacuated tube collector contains two heat pipes that pass through one of the centres of the tube. One pipe will work as an input fluid pipe and the other works as an output fluid pipe. Both two pipes are allied together at the bottom of the tube with a "U shaped-bend". Both two tubes are vacuum wrapped into a glass tube for appropriate insulation. The procedure is the same as that of flat plate collectors, excluding the vacuum given by the outer tube. The tubes are difficult to replace as fluid flows inside and outside of each tube. This collector will need to carry on continuous draining as there will be a "wet" connection between the manifold and tube. Numerous Professionals of the solar industry trust the direct flow evacuated tube designs as those that add more energy efficiency in design than heat pipe design because, in the case of direct flow, it does not contains a heat exchange among fluids, and there is no requirement of a solar tracking system.

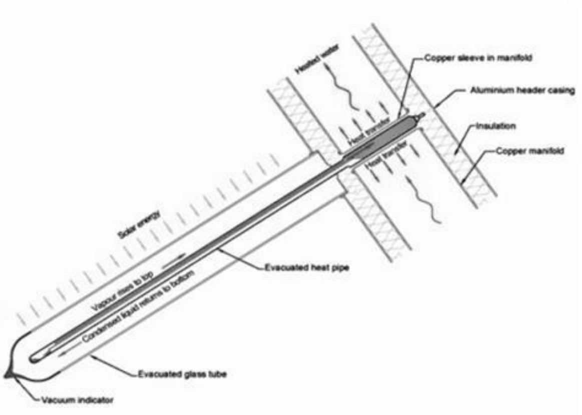

Figure 1Evacuated Tube Operation

THERMAL ANALYSIS OF EVACUATED TUBE COLLECTORS

Based on the input and output parameters of the evacuated glass tube solar collector, we can find the system's overall efficiency. The thermal efficiency is defined according to the following equations.

Solar energy collected by solar collector:

$$Q_1 = \dot{m}C_p(T_2 - T_1) \qquad (1)$$

Solar collector Efficiency:

$$\eta_c = \frac{\dot{m}C_p(T_2 - T_1)}{AG} \qquad (2)$$

Losses in supply pipe:

$$Q_2 = \dot{m}C_p(T_3 - T_1) \qquad (3)$$

The energy delivered to working fluid:

$$Q_3 = \dot{m}C_p(T_3 - T_4) \qquad (4)$$

Solar Fraction:

$$SF = \frac{Q_y}{Q_y + Q_{hr}} \qquad (5)$$

Overall system efficiency:

$$\eta_s = \frac{\dot{m}C_p(T_3 - T_4)}{AG} \qquad (6)$$

Where,

Q_1 = Useful Heat Collected (J)

m = Mass Flow Rate of Solar Fluid (kg/s)

C_p = Specific Heat Capacity of Solar Fluid (J/(kgK))

T_1 = Collector Inlet Temperature (^oC)

T_2 = Collector Outlet Temperature (^oC)

η_c = Collector Efficiency (%)

A = Collector Area (m^2) = Tube Diameter * Length of Tube * No. of Tube

G = Solar Radiation on the Collector (W/m^2)

Q_2 = Useful Heat Delivered (J)

Q_3 = Supply Pipe Heat Loss (J)

T_3 = Working Fluid Inlet Temperature (^oC)

T_4 = Working Fluid Outlet Temperature (^oC)

SF = Solar Fraction (%)

Q_y = Solar Yield (MJ)

Q_{hr} = Heating Requirement (MJ)

η_s = System Efficiency (%)

REVIEW

The performance enhancement of the evacuated tube solar collectors have been studied and reported before. According to that, the performance of individual components and the arrangement influence the overall performance of the solar collector. A good quality Selective coating on absorber plate with low emittance and solar absorbance above 90 per centshould reduce radiative energy losses(3). G.L. Morrison studied various designs of heat condenser manifold in a single-ended evacuated tube like the fluid-in-glass, fluid-in-metal and Metal-in-glass because, in evacuated tube collectors, the major difficulty is to extract heat from the evacuated tubes (4). New technologies have been developed to enhance the thermal performance of evacuated tube collectors, which involve heat transfer from absorber tube to the working fluid, changing the structures of solar collectors, coating on absorber tube, using nanofluid as working fluid, collector tilt angle in different industrial applications (5), (6). Inlet temperatures, flow rates in manifold and tube inclination angles for a wide range of operating conditions resulted in high heat transfer efficiency (7). Experimental results of mass and thermal flow rate on solar hot water systems revealed that the energy collection would be reduced for a higher flow rate (8). The heat pipe ETSC is more efficient than the FPC of a solar water heating system because it produces a high temperature, but the initial cost of ETSCs is higher than FPC(9). All evacuated tubes are the cheapest, simplest and more cost-effective than the electric water heater with 50° C operating temperature, suitable for domestic applications. In addition, as the tube collectors are directly connected with the tank, the heat loss is less(10). Heat production at a medium and high-temperature level for industrial processes is one of the most critical applications. A solar thermal energy system requires storage into industrial applications so that the system can operate in a non-continuous supply of solar energy periods and nighttime(11).

SUMMARY

Hence the factors which affect the performances are as following,

1. Angle:

The inclination angle is the main part of solar absorptance capacity in the evacuated tube solar collector system. The radiation of solar ray's and heat gain are affected mainly by the inclination angle. Many researchers discussed the effect of inclination angle on the performance of solar ETCs. That inclination angle does not significantly impact the efficiency of ETCs, but still, the range should be appropriately selected. The range could be 25˚-30˚for higher thermal efficiency.

Table 2 Inclination Angle

Name	Year	Author	Type	Summary
The Effect of the Angle of Inclination on the Efficiency in a Medium-Temperature Flat PlateSolar Collector	2017	Orlando Montoya-Marquez and José Jasson Flores-Prieto	Experimental	• The effects of varying the inclination angle are reflected directly in the overall loss coefficient, which significantly affects the thermal efficiency. (12) • Variations behave almost linearly over the inclination range with

				respect to the average value. (12)
Thermal performance of an investigation of evacuated tube heat pipe solar collector with nanofluid	2016	N. H. Mujawar, S. M. shaikh	Experimental	• Used nanofluid and compared with conventional working fluid pure water in the collector. • The thermal performance of nanofluid is obtained, which is higher than pure water. • For different tilt angles and mass flow rates, efficiency is measured. • The best performance can be obtained at a 30° tilt angle and 20 LPH flow rate for both collectors. (13)
Effect of inclination Angle on Temperature characteristics of water in glass evacuated tube	2017	Sheetal Kanthekar, Priya Rai, A.V. Joshi	Experimental	• For inclination angles 15°,30°and 45°, the collector performance was measured experimentally. (14) • PT 100 thermocouple used for the measuring temperature. • For a lesser inclination angle, the highest temperature can be obtained. (14)
Effect of inclination angle on temperature characteristics of water in glass evacuated tubes of domestic solar water heater	2012	P. selvakumar, Dr. P. somasundaram	Experimental	• For different inclination angle 0°,15°,30°,45°,60° and 90°, the temperature of the top, bottom and middle of the tube is measured. • It observed that inclination angle and facing direction is not produced a significant effect on temperature value. (15)

2. Working fluid:

The thermal conductivity of conventional fluids like water, oil, and air is relatively low, so the system's thermal efficiency also decreases. So to improve the thermal performance of ETSC, the researchers are currently working on nanofluid as a working fluid. Because nanofluids consist of base liquid and nanomaterials that have enhanced thermophysical properties such as higher thermal conductivity, thermal diffusivity, and convective heat transfer coefficients. Besides improving heat transfer effectiveness, nanofluids also improve optical properties, transmittance, and the extinction coefficient of solar collectors.

Researchers have used different nanofluid such as MWCNT/Fe3O4, Cupper oxide/ distilled water, Al2O3 and CuO/acetone, single-walled CNT and methanol from all above researchers found that the thermal performance of nanofluid is obtained which higher than the pure water.

Table 3Working fluid

Name	Year	Author	Type	Summary
Thermal performance of an investigation of evacuated tube heat pipe solar collector with nanofluid	2016	N. H. Mujawar, S. M. shaikh	Experimental	• Used nanofluid and compared with conventional working fluid pure water in the collector. • The thermal performance of nanofluid is obtained, which is higher than the pure water. • For different tilt angles and mass flow rate measured efficiency. • The best performance can be obtained at a 30° tilt angle and 20 LPH flow rate for both collectors. (13)
Performance assessment of evacuated U-tube solar collector: a numerical study	2019	B kirannaik, P muthu kumar	Numerical study	• For working fluid (water, air) and collector material (brass, copper and aluminium), the effect of heat gain can be experimented with. • It observed that the outlet temperature of copper is higher than the of brass and aluminium. So working fluid like water or air the copper is selected because of high thermal conductivity. (16)
Novel solar collector: Evaluating the impact of nanoparticles added to the collector's working fluid, heat transfer fluid temperature and flow rate	2019	Hassan Fathabadi	Experimental	• A prototype has been built, and experimental data is obtained from that. • To determine the effect of nanoparticles, distilled water and CuO-H2O nanofluids with 0.5%, 1%, 1.5%, 2%, 2.5%,3% and 3.5% nanoparticles weight percentages were used as the working fluids charged inside the two-phased closed thermosiphon (TPCT). • Adding CuO particles up to 1.5% distilled water enhanced the thermal efficiency of the collector. (17)

Performance evaluation of flat plate and vacuum tube solar collectors by applying an MWCNT/Fe3O4 binary nanofluid	2020	Minjung Lee, Yunchan shin, Honghyuncho	Numerical study	• Experimentally investigated binary nanofluid as a working fluid in a flat plate and vacuum tube solar collectors. (18) • When binary nanofluid was used as a working fluid in both flat and evacuated tube collectors, the efficiency is increased. (18)
Thermal characteristics of evacuated tube solar collectors with coil inside: An experimental study and evolutionary algorithms	2019	GholamabbasSadeghi et al.	Experimental	• They are worked on the different volumetric flow rates of fluid-like 10, 30, 50 LPH and copper oxide/distilled water as a nanofluid. • They also observed that as the flow rate and concentration of the nanofluid increased, the efficiency also increased. (19)
Improving the performance of heat pipe evacuated solar tube collector experimentally by using Al2O3 and CuO/acetone nanofluids	2018	Adel A. Eidan, Assaad Alsahlani et al.	Experimental	• They analyzed for two types of nanofluid Al2O3 and CuO / acetone. • They observed that for inclination angle 45˚ and filling ratio of 70%, the optimum efficiency was obtained. • For volumetric concentrations of 0.25% and 0.05%, the highest efficiency is observed for both the nanofluids. (20)
Experimental study of a hybrid evacuated solar tube collector using methanol as working fluid	2018	J. Ferdous, M.R.I. Sarker, R. A. Beg	Experimental	• They worked on the design, fabrication and experimental investigation of a hybrid evacuated tube collector. (21) • To minimize the compressor power, ETC was attached to the air cooler. • They used methanol as a working fluid in heat pipe ETC.(21)
CFD analysis of evacuated tube heat pipe solar water heater	2017	Prof. V. Y. Chaudhary, Bharat Kalamkar et al.	Simulation	• Working fluid as a nanofluid is obtained the higher thermal conductivity rather than the working fluid as water. That mainly occurred due to the lower temperature between the evaporator and condenser in a nanofluid. (22)

3. Design of condenser:

The vapour rises to the tip of the heat pipe, and then heat is transferred to the water flowing through the manifold. Due to this, heat transfer vapour will condense then flow back down the heat pipe by the condenser so that this process will be repeated. Researchers have not worked on the design of the condenser. But condenser is the main part for heat transfer nanofluid to the working fluid water. So with the help of the design structure such as rectangular shape and fin structured condenser, the performance should be increased.

4. Coating:

The coating is generally used for improving the performance of ETSCs. Because of the coating, better solar radiation absorption and minimal reflection property are obtained. Researchers worked on coating for glass tubes, and they found that the value of absorptivity is increased as with coating used. No significant effect is observed for three different values of the aluminium fin thickness due to the constant value of absorptance, but the heat loss coefficient and heat removal factor is increased with decreasing the thickness.

Table 4 Surface Coating

Name	Year	Author	Type	Summary
Review of materials for solar thermal collectors	2005	M. A. Alghoul, M. Y. Sulaiman, B. Z. Azmi and M. Abd	Review	• In an evacuated tube collector, the outer tube is made from borosilicate. The inner tube is also made from borosilicate but coated with aluminium which has good solar heat absorption and minimum heat reflection properties. (1)
Thermodynamic analysis of factors affecting the performance of solar collectors	2017	Arvind kumar, shivlal, Harender	Experimental	• Higher the difference between the absorber plate temperature and ambient temperature results in higher heat losses. • For the Higher value of absorptivity, a surface coating is used over the absorber tube. • The higher the tank temperature greater will be the heat losses. (24)
Effects of Aluminium Fin thickness coated with a solar paint on the thermal performance of evacuated tube collector	2017	Amanuel Andemeskel, Tawat Suriwong,warisawamae	Experimental	• For three aluminium Fin thicknesses, 11µm, 13µm and 24µm thermal performance are observed. • No significant effect is observed in different thicknesses because solar absorptance α is 0.94 for all thickness values.

				• It observed that the heat loss coefficient and heat removal factor is increased with decreasing the thickness. (25)
Performance evaluation and analyses of novel parabolic trough evacuated collector tubes with spectrum selective glass envelope	2019	Qiliangwang, Mingke Hu et al.	Experimental	• Based on the characteristic of uneven distribution of solar irradiation. (26) • around the absorber tube, a novel parabolic trough evacuated tube collector tubes with IR-reflectors coated on the surfaces of the glass envelope in the non-concentration (26)

5. Flow rate:

Flow rate is mainly used for increasing the temperature. To optimize the value of mass flow rate for better performance of the system. It observed that the outlet temperature is highly influenced by the mass flow rate of working fluid and proportional to solar density. Many researchers worked on different values of flow rate. From that, researchers suggested that for the 20LPH flow rate, the optimum result could be obtained. It also observed that the higher the value of mass rate is reduced the efficiency of solar evacuated tube collector due to the higher heat losses.

Table 5 Flow Rate

Name	Year	Author	Type	Summary
Thermal performance of an investigation of evacuated tube heat pipe solar collector	2016	N.H.Mujawar, S.M.shaikh	Experimental	• The thermal performance of nanofluid is obtained, which is higher than the pure water. For different tilt angles and mass flow rate measured efficiency. • The best performance can be obtained at a 30° tilt angle and 20 LPH flow rate for both collectors. (13)
Performance assessment of evacuated U-tube solar collector: a numerical study	2019	B kirannaik, P muthukumar	Numerical study	• For working fluid (water, air) and collector material (brass, copper and aluminium), the effect of heat gain can be experimented with. • It observed that the outlet temperature of copper is higher than the of brass and aluminium. So working fluid as water, air or copper is selected because of high thermal conductivity. • Up to 1.6m collector length, the amount of

				heat absorbed by water also increased as the flow rate increased. (16)
Novel solar collector: Evaluating the impact of nanoparticles added to the collector's working fluid, heat transfer fluid temperature and flow rate	2019	Hassan Fathabadi	Experimental	• A prototype has been built, and experimental data is obtained from that. • To determine the effect of nanoparticles, distilled water and CuO-H2O nanofluids with 0.5%, 1%, 1.5%, 2%, 2.5%,3% and 3.5% nanoparticles weight percentages were used as the working fluids charged inside the two-phased closed thermosiphon (TPCT). • Adding CuO particles up to 1.5% distilled water enhanced the thermal efficiency of the collector. • It also found that an increase in HTF temperature decreased the thermal efficiency of the collector, while increased inflow rate enhanced the thermal efficiency. (27)
Experimental study of a hybrid evacuated solar tube collector using methanol as working fluid	2018	J.Ferdous, M.R.I. Sarker, R.A.Beg	Experimental	• To minimize the compressor power, ETC was attached to the air cooler. • They used methanol as a working fluid in heat pipes ETC. • For mass flow rate value of 0.00188kg/s, they have obtained the highest efficiency of about 28.69%. (21)
Optimization of evacuated tube collector parameters for solar industrial process heat	2017	Adel A. Ghoneim	Numerical Analysis	• Length 0.5m to 2.5m and diameter 30mm and 60mm the thermal efficiency is measured. • The optimum tube length is 1.5m and 30mm diameter, so a significant enhancement in thermal efficiency is observed. • The optimum value of mass flow rate is 30kg/h.m2 efficiency is increased. (28)
Evaluation of thermodynamic Analysis of solar energy systems integrated into	2019	A. Enda Tolon, Arif Karabuga et al.	Numerical Analysis	• The change of exergy efficiency depended upon the radiation, ambient temperature, and the flow rate was investigated. • It also found that when the ambient temperature and mass flow rate increased,

sustainable buildings with the artificial neural network: a case study				the exergy efficiency was decreased. (29)
Thermodynamic and techno-economical analysis of heat pipe ETC water heating system for Indian composite climate	2019	K Chopra, et al.	Numerical Analysis	• The experimental investigation is carried out for the different mass flow rates of water. (30) • The maximum and minimum average outlet temperature from the collector was 76.4° and 45° for 20LPH and 60LPH water mass flow rate, respectively. (30)
Experimental investigation of solar desalination system using evacuated tube collector	2019	Shridhar Kedar, Arul raj Kumaravel et al.	Experimental	• Maximum inner surface glass and formation of steam temperature were observed about 112- 115˚ C. Outlet distillate temperature 62-64˚C observed at 16.00 h for 0.01 lps and 0.02 lps mass flowrate. • Wind effect on the formation of soft water found was very low. • So 25-27 litres of soft water per day was obtained. (31)

CONCLUSION

The present paper gives a broad overview based on recent updates related to nanofluids in heat pipe solar operated collectors.

This paper presented an overview of recent studies on ETSCs and revealed that this collector has excellent potential in the industrial, residential and agricultural sectors. An ETSC is highly recommended for higher temperature applications as they can gain higher temperatures quickly. Some recommendations are made for future research work. It is expected that it will be very useful for energy-producing industries as well as for research organizations. Multi-objective optimization techniques should be adopted for performance enhancements. Additionally, there should be a focus on the structure and material of the manifold in future research.

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