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Optimization of thermal efficiency of a parabolic trough solar collector (PTSC) based on new materials application for the absorber tube selective coating and glass cover

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Abstract: This article aims to demonstrate a solution in order for an optimization of PTSCs thermal efficiency. The solution focuses on the radiative heat transfers occurring within the absorber tube of a PTSC unit of a solar power plant situated in Shiraz, Iran as the paper case study. Since the existing heat transfers procedure all comes down to the optical properties of the materials used in the absorber tube of a PTSC unit, an ideal material selection can directly influence the heat transfers and consequently improve the thermal efficiency of a PTSC unit to a great extent. This paper comes up with new materials selection in which graphene nanostructure and BOROFLOAT 33 are respectively used as absorber tube coating and absorber tube glass cover for their exceptional optical and mechanical properties. Meanwhile, a numerical and analytical comparison is made between the thermal efficiencies of a PTSC unit in different states.

Keywords: Coating; Glass Cover; Material; PTSC; Solar; Thermal Efficiency

1. INTRODUCTION

Since 2016 has recently been announced by the scientists as the hottest year ever recorded, greenhouse gases have made scientists avoid dirty energy based technologies more than ever before. Therefore, increasing worries about global warming and its inevitable consequences have pushed many scientists to step up their efforts towards conducting more researches into clean energies. In fact, the sun is one of these energy resources which is considered as a source of a renewable and environmentally friendly energy. As far as the need for electricity is concerned, solar energy is an appropriate substitute for other energy resources which are harmful to the environment, in order to produce electricity. There are various ways to produce electricity from solar energy. One of the ways is to use Parabolic Trough Solar Collector (PTSC) in which solar energy is indirectly converted into electricity. Nowadays, PTSCs are used in solar power plants in large number in order to produce a great deal of electricity along with no types of pollution. Scientists have always been attempting to heighten the thermal efficiency of PTSCs. There are many factors which are influential in increasing the thermal efficiency of PTSCs, including the convective heat transfer coefficient of the relevant fluids, and the optical and thermal properties of the materials applied in PTSCs systems. In his previous work, the author focused on the considerable influence of the

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convective heat transfer coefficient of the relevant fluids on the thermal efficiency of PTSCs. In this paper, the attention is drawn to the selective coating of a PTSC absorber tube and its glass cover material whose optical properties play a crucial role in optimizing the thermal efficiency of PTSCs. In this study like the previous work, the PTSCs of the solar power plant situated in Shiraz, Iran is considered as the paper case study. Table 1 presents the specifications of the case study (Yaghoubi, 2013). In the previous work, some solutions in order to raise the thermal efficiency of PTSCs were theoretically discussed through creating some conditions based on the convective heat transfer coefficient of the relevant fluids (Jamali, 2016). In the current research, it is numerically and theoretically analyzed how the thermal efficiency achieved in the author's previous work would be re-optimized based on the absorber tube selective coating and the glass cover material in order to gain a higher thermal efficiency. In the author's previous work, three prominent forms of absorber tube internal enhancements, which are tube with twisted tape inserts, corrugated tube, and internally finned or ribbed tube, were studied and also applied to a PTSC equipped with vacuum glass cover in order to optimize the thermal efficiency of PTSC through convective heat transfer coefficients of the relevant fluids (Jamali, 2016). The current study is a re-optimization of the thermal efficiency achieved in the previous study based on the radiative heat transfers occurring at the PTSC unit. The thermal efficiency of the above-mentioned PTSC can be calculated by the following equation (Jamali, 2016):

$$\eta_{Thermal} = \frac{q_{SolAbs} - q_{ThermalLoss,g}}{AG_s} \qquad (1)$$

Where $q_{SolAbs} - q_{ThermalLoss,g}$ is calculated as follows (Jamali, 2016):

$$q_{SolAbs} - q_{ThermalLoss,g} = q_{rad-a-g} + q_{conv-fluid} - q_{rad-g-sky} - q_{conv-g-air} \qquad (2)$$

Considering equations (1) and (2), it is simply deduced that the higher the absorber tube emissivity is and also the lower the glass cover emissivity is, the higher the PTSC thermal efficiency is. In other word, an efficiency optimization will be obtained by selecting an absorber tube coating with high emissivity and absorptivity, and low reflectivity at the same time, and on the other hand, by selecting a glass cover with low emissivity and high transmissivity. Since a blackbody is an ideal absorber, i.e., a blackbody does not reflect or transmit any incident electromagnetic radiations, and at the same time in thermal equilibrium with the environment, emits energy at the same rate that it absorbs energy. In this paper, a perfect blackbody based on graphene nanostructure is considered as an ideal candidate for an absorber tube coating. This blackbody material of graphene nanostructure was fabricated via anisotropic hydrogen plasma etching in a microwave (Frequency: 2.45 GHz) plasma-assisted chemical-vapor-deposition apparatus (Matsumoto, Koizumi, Kawakami, Okamoto, & Tomit, 2013). The typical etching conditions are as follows: a microwave power of 800 W, a gas pressure of 1.3 kPa, an H_2 gas flow rate of 80 sccm, a substrate temperature of 600℃, and an etching time of 30 min (Motsumoto & Mimura, 2004; 2005). In this case, a carbon substrate was positioned on the cathode electrode, and the substrate was sputtered in ambient H_2 or Ar gas at a pressure of 30 Pa and a power of 600 W for a sputtering time of 30 min (Shiozawa et al., 2007). Graphene is a two-dimensional crystal characterized by a high quality and a continuous structure on microscopic scale (Novoselov et al., 2005). Graphene is made of carbon atoms each of which has four valence electrons (Pawel, 2012). Bonds between adjacent atoms are formed from three valence electrons on s, p_x, and p_y atomic orbitals (Pawel, 2012). The hybrid orbitals are responsible for a structural stability of a graphene layer (Pawel, 2012). The fourth valence electron is on the p_z orbital that is orthogonal to the graphene plane, which is weakly bound and determines electronic properties of the system (Pawel, 2012).Since it is always necessary to make a trade-off between efficiency and cost, chemical vapor deposition (CVD) can be decided as a cost-effective and scalable method especially regarding the amount of the selective coating applied to the absorber tube of a parabolic trough solar collector (Zhang, Li, Kim, Zhang, & Zhou, 2012). As the absorber tube of PTSC is made of stainless steel, this material substrate can be considered as a relatively inexpensive substrate to be economical for the deposition of carbon on it and then the synthesis of graphene nanostructure on the carbon film substrate. By CVD technique it is possible to transfer graphene layers samples to an arbitrary substrate, e.g by using dry-transfer process (Pawel, 2012). The dry transfer process enables the transfer of large area and high quality graphene film

(Caldwell et al., 2010). To improve the bonding strength between the transferred graphene film and the handle substrate, a cleaning and surface preparation procedure is used (Caldwell et al., 2010). From optical viewpoint, graphene nanostructure shows an emissivity and an absorptivity higher than 0.99, and a reflectivity less than 0.01 over a wide range of electromagnetic wavelengths, from 400 nm to 2 μm (Matsumoto et al., 2013).In terms of mechanical properties, graphene as the single layer of the graphite crystal, one atom thick, is extremely strong in tension and bends very easily while resisting getting torn by any internal or external agents (Wolf, 2014). It is also heat resistant and does not undergo any degradations even in the temperatures up to 2600 K (Matsumoto et al., 2013). The aforementioned properties are absolutely quintessential to keep the lifetime of a PTSC power plant long enough.

In terms of the application of the glass cover material, a new glass material called BOROFLOAT 33 is demonstrated in the paper to be used instead of the currently used glass cover material of the case study that is Pyrex glass. This is an industrial glass material which has more ideal properties in favor of PTSC thermal efficiency in comparison with Pyrex glass. In other words, while the emissivity of Pyrex glass is 0.92, the emissivity of BOROFLOAT 33 is negligible for UV range and a small part of visible range (AG, BOROFLOAT 33, 2017). Which is favorable regarding the fact that the wavelength of UV spectrum reaching the earth's surface ranges from 290 nm to 400 nm and the excitation wavelength of BOROFLOAT 33 is 488 nm. Table 3 shows the other properties of the two materials.

Therefore regarding the new materials demonstrated above, a new study of the thermal efficiency of a new PTSC is conducted based on the existing radiative heat transfers.

Additionally, a literature review on solar selective black coatings produced to be applied in solar thermal systems is mentioned below in order to help figure out the progress already made in this regard. It should be noted that, in this article, the solar absorptivity and thermal emissivity as the radiative heat transfer properties of the black coatings are mainly focused since the high values of them are mostly effective and in favor of a PTSC thermal efficiency. There are many different black coatings which have been studied by several authors so far, in order to be used in solar absorbers surfaces:

Electrolytic coatings such as black chromium or black nickel, in combination with highly infrared reflecting solar absorber was developed by Tabor over 40 years ago (Zvi, 1959).

In an study by Anandan et al, solar selective black chromium electrodeposited on pre-treated electroformed nickel substrates from a hexavalent chromium coating bath was investigated before and after annealing at 400 ℃ for different durations, in order to improve the solar selective properties of the coating (Anandan, 2002). The optical properties of chromium black coatings prepared by electrodeposition were presented by Bahaghel et al in which the values of absorptivity and emissivity were 0.97 and 0.1 respectively (Behaghel, Berthier, Lafait, & Rivory, 1979). By preparation of nickel-black selective surfaces on zinc-plated steel, galvanized iron, zincated aluminium, and zincalume, solar absorptivities ranging from 0.9 to 0.94 and thermal emissivities ranging from 0.08 to 0.15 can be obtained (Cathro, 1981). Black chrome absorber coatings have been developed by CVD-technique involving deposition of chrome hexacarbonyl (Erben, 1985). The black substrates can provide absorber-reflector tandems with good selective properties, as reported by Muehlratzer et al. (Erben, Bertinger, Mühlratzer, Tihanyi, & Cornils, 1985). The black nickel chrome absorber coatings demonstrated a significant solar absorptivity of 0.95 and an emissivity of 0.1. The coatings deposited on steel substrates have remained intact after 1000 h of lifetime testing in air at 600 ℃.

Choudhury et al. have studied the growth of black cobalt selective surfaces on galvanized iron substrates which gave the absorptivity and emissivity of 0.91 and 0.12 respectively (Choudhury & Sehgal, 1982). Cindrella et al. studied the effect of the an additive (1,2,3-benzotriazole) on the coating parameters. They used a new complexing agent (ammonium acetate) for the development of selective black coatings (Cindrella, Sooriamoorthy, & John, 1991). The optimized coatings possessed a solar absorptivity of 0.96 and a thermal emissivity of 0.12. Ebrahimi et al. introduced a technique to make a ultra-black surface by employing nanoporous anodized aluminum oxide as a template and deposition of nickel-phosphorous nanowires by the electroless process (Ebrahimi, Yazdi, Najafabadi, & Ashrafizadeh, 2015). The results showed that ultra-black duplex coating possessed an absorptivity higher than 0.99 and an emissivity about 0.6.

Black chromium selective solar absorber coatings deposited by sputtering and electrodeposition have been studied by Holloway et al. after heat treating (Holloway, Shanker, Alexander, & Sedas, 1989). Both sputter-deposited $Al_2O_3 - Cr$ and electrodeposited $Cr_2O_3 - Cr$ black chromium coatings degrade at temperatures below 400 ℃ by oxidization of chromium to Cr_2O_3 in the coating.

A new electrolyte has been proposed by John et al. for the deposition of black cobalt selective absorber coatings (John, 1991). The absorptivity and emissivity of the coating produced under the optimum conditions were found to be 0.96 and 0.12 respectively.

John has also produced an electrodeposited black nickel solar absorber coating cathodically from a low concentration bath (John, 1997). The optical properties of the coating were found to be α =0.96 and ε=0.11.

Joly et al. produced multilayered chrome-free black selective surfaces by a low-cost sol-gel dip-coating method (Joly et al., 2013). A solar absorptivity of 0.95 and a thermal emissivity of 0.12 at 100 ℃ have been achieved after optimization of the multilayer design.

Copper cobalt manganese silicon oxides as black selective coating were also investigated by Joly et al. (2015). A three-layered coating deposited on stainless steel substrates exhibited a solar absorptivity of 0.96 and a thermal emissivity of 0.12 at 100 ℃.

Electrodeposited black nickel coatings plated from chloride baths on metallic substrates have high solar absorptivities (>0.92) and low thermal emissivity (<0.15) (Koltun, Gukhman, & Gavrilina, 1994).

Kumar et al. has developed an economically viable electroless process to deposit nickel black coating on galvanized iron which gave absorptivities ranging from 0.9 to 0.93 and an emissivity of 0.073 at 100 ℃ (Kumar, Malhotra, & Chopra, 1980).

An optimum black chrome coating was made on Ni substrates using a newly synthesized electrolyte by Lee et al, which had an absorptivity ranging from 0.9 to 0.96 and an emissivity ranging from 0.25 to 0.3 (Lee, Jung, & Kim, 2000).

The effects of pulse current (PC) electrolysis during electrodeposition of black chrome oxide (Cr_2O_3) on the optical properties and surface microstructure of the solar selective coatings were investigated by Lee, Kim, Cho, and Chungmoo Auh (1991). An absorptivity of 0.973 and an emissivity of 0.17 were achieved for PC-applied initial (as deposited) black chrome coatings by this method.

Lira-Cantú et al. worked on electrochemical deposition of nanostructured nickel-based solar absorber coatings on stainless steel AISI type 316L (Lira-Cantú, Morales Sabio, Brustenga, & Gómez-Romero, 2005). The best solar absorptivity and thermal emissivity values obtained were 0.91 and 0.1 respectively.

A solar selective black nickel-cobalt coating has been formed on zincated and zinc-electroplated aluminium substrates by Mehra and Sharma (1988). An absorptivity ranging from 0.9 to 0.94 and an emissivity ranging from 0.07 to 0.12 have been achieved.

The properties of black chrome coatings on electrodeposited zinc and Zn-Co alloy with the presence of certain additives have been investigated by Nikolova, Harizanov, Steftchev, Kristev, and Rashkov (1988). Absorptivities ranging from 0.88 to 0.9 and ones ranging from 0.9 to 0.93 were obtained for zinc substrate and Zn-Co substrate respectively.

Solar selective black zinc coatings on zinc-electroplated aluminum substrates were investigated by Patel and Ianl, which yielded an absorptivity of 0.954 and an emissivity 0.101 (Patel & Inal, 1984). In addition, black nickel selective solar surfaces were produced from a nickel chloride bath with additives of zinc chloride, ammonium chloride, and sodium thiocyanate, which yielded an absorptivity of 0.95 and emissivities ranging from 0.24 to 0.26 (Patel, Inal, Singh, & Scherer, 1985).

Pettit has discussed the accelerated aging of electrodeposited black chrome coatings deposited onto nickel substrates (Pettit, 1983). The solar absorptivity initially remains unchanged at values ranging from 0.96 to 0.97 and then begins to gradually decrease with continued aging to values below 0.9.

Pillai and Agarwal have investigated on spectrally selective coatings of black chrome prepared by spraying an aqueous solution of CrO_3 onto chemically brightened aluminium substrates heated 250 ℃ − 300 ℃ (Pillai & Agarwal, 1980). The coatings had an absorptivity of 0.93 and an emissivity of 0.16.

Solar selective black nickel-cobalt plating on pre-cleaned aluminum alloy substrate with nickel undercoat has been investigated by Saxena, Rani, and Sharma (2006). An absorptivity of 0.948 and an emissivity of 0.17 were obtained.

Therefore, comparing the solar absorptivity and thermal emissivity of graphene nanostructure (in the form of nano-needles) as 0.99 which are the highest ones and also its specular reflectivity as 0.01 which is the lowest one ever achieved with the ones of the studied materials in the above-mentioned literature, it is obviously observed that graphene has the most ideal radiative heat transfer properties among all materials and consequently gives the best PTSC thermal efficiency in terms of coating selection, regarding equations (1), (2), and (3).

Since the thermal efficiency of a PTSC unit as a thermal system is directly influenced by the solar selective coatings used in the PTSC unit, the PTSC thermal efficiency can be optimized by employing appropriate selective coatings. A selective absorber surface without a vacuum glass cover, for successful operational use in solar thermal systems, must possess as many of the following characteristics as possible: high solar absorptivity, low thermal emissivity, large angle of acceptance, long-term stability at desired operating temperatures and environmental conditions, stability to (or recovery from) short-term overheating due to failure extract energy from the collector, stability in the presence of moisture, durability for the life of the collector, applicability to the given substrate materials, reproducibility, and reasonable cost. While, as mentioned above, a selective absorber surface without vacuum glass cover must have an emissivity as low as possible, a selective absorber surface equipped with a glass vacuum glass cover needs to have an emissivity as high as possible in order to yield a higher thermal efficiency (Jamali, 2016). It should be mentioned that in both selective absorber surface without vacuum glass cover and one with vacuum glass cover, a surface absorptivity as high as possible is needed.

2. ABSORBER TUBE SELECTIVE COATING

With an emissivity and an absorptivity higher than 0.99, and a reflectivity less than 0.01 over a wide range of electromagnetic wavelengths, from 400 nm to 2 μm, graphene nanostructure (Matsumoto et al., 2013) can be considered as an ideal blackbody material in order to be used as the selective coating of an absorber tube. In this section, a comparison is made between the optical and mechanical properties of the selective surface coating which is currently used in the absorber tubes of the solar power plant situated in Shiraz, Iran as our case study, and a new one, i.e., graphene nanostructure. Black chrome coating as the most widely used cermet coating has been being used in the absorber tubes of the above-mentioned solar power plant so far. Black chrome absorber coating has been developed by CVD technique (Erben, 1985). The coating deposited on steel substrate has shown to remain intact after 1000 h of lifetime testing in air at 600 °C (Erben, 1985). Table 2 shows the essential properties of the two selective coatings discussed above.

As shown in table 2, the values of all the properties of deposited graphene nanostructure are considerably higher than those of deposited black chrome. Therefore, these differences between the values of the two materials properties can guarantee a higher thermal efficiency by application of the new material, i.e., graphene nanostructure instead of the currently used material, i.e., black chrome in the case study, according to equations (1) and (2). The radiative heat transfer between the absorber tube and the glass cover of a PTSC can be calculated by the following equation (Bergman, Incropera, DeWitt, & Lavine, 2011):

$$q_{rad-a-g} = \varepsilon_a \sigma \left(T_{s,a}^4 - T_{g,s}^4\right) \tag{3}$$

3. ABSORBER TUBE GLASS COVER MATERIAL

Since the convective heat transfer between the absorber tube of a PTSC and the air around it, $q_{conv-a-air}$, will result in PTSC thermal loss, a vacuum glass cover becomes a quintessential part of a PTSC in order to minimize this unfavorable effect and consequently raise the thermal efficiency of a PTSC (Jamali, 2016). Since the optical and mechanical properties of a glass cover material play an important role in both efficiency and cost, selecting an appropriate glass cover material becomes a crucial part of the job in order to raise the thermal efficiency of a PTSC. An ideal material for a glass cover would have the following properties:

- Low light emissivity
- High temperature durability and long lifetime when exposed to UV radiation
- Good light transmissivity
- Good impact resistance
- Light weight and easy to work
- Opaque to LWIR radiation in order to reduce heat loss
- Low cost

There is certainly no single material which exhibits all of the above-mentioned properties; therefore picking the best material for its application would be a trade-off between these properties. In the previous study conducted by the author on the thermal efficiency of the PTSCs of the solar power plant situated in Shiraz, Iran, the properties of Pyrex glass cover as its currently used glass cover were applied in the calculations (Jamali, 2016). In this study, BOROFLOAT 33 as a comparatively selected material is decided to be applied for an absorber tube glass cover. BOROFLOAT 33 is an industrial glass with lowest level of iron impurity of all float glass materials in the market (AG, BOROFLOAT 33, 2017). As a matter of fact, its low inherent fluorescence emissivity, exceptionally high transparency, outstanding transmissivity in UV, visible, and NIR wavelengths makes it an ideal material selection for an absorber tube glass cover. Other outstanding properties of BOROFLOAT 33 are also comparatively shown along with the properties of Pyrex in table 3. Accordingly, the new material brings about an improvement in the radiative heat transfer between the glass cover and the sky, which is in favor of PTSC thermal efficiency. The radiative heat transfer between the glass cover and the sky can be calculated by the following equation (Bergman et al., 2011):

$$q_{rad-g-sky} = \varepsilon_g \sigma \left(T_{g,s}^4 - T_{sky}^4\right) \quad (4)$$

In this paper, BOROFLOAT 33 with an excitation wavelength of 488 nm is considered. This excitation wavelength shows that there is no fluorescence emissivity for the wavelengths shorter than 488 nm. Therefore, the fluorescence emissivity of BOROFLOAT 33 for UV range and a small part of visible range is negligible, while it starts to increase up to 40% with increase in visible wavelength and then starts to decrease in a small part of visible and IR range with increase in wavelength (AG, BOROFLOAT 33, 2017). Regarding the fact that the wavelength of UV spectrum that reaches the earth's surface is in wavelengths between 290 nm and 400 nm, BOROFLOAT 33 is more than 90% transmissive to the received UV spectrum (AG, BOROFLOAT 33, 2017). It starts to lose its transmissivity after the wavelengths higher than UV range (AG, BOROFLOAT 33, 2017). This procedure continues until it becomes nearly opaque to the wavelengths about 5000 nm that is within MWIR range (AG, BOROFLOAT 33, 2017). Therefore BOROFLOAT 33 proves to demonstrate a good greenhouse effect, which is in favor of PTSC thermal efficiency. Table 4 shows the range of the wavelengths of the relevant electromagnetic spectra.

Table 1. Specifications of a unit of the studied PTSC.

Absorber tube inner diameter	$\mathbf{6.56\ cm}$	**Inner diameter of glass tube**	$\mathbf{11\ cm}$
Absorber tube outer diameter	$7\ cm$	Sun angle	**28.92°**
Collector aperture Area (A_a)	$25\ m \times 4.3\ m$	Solar irradiation (G_s)	**836** $\mathbf{W/m^2}$
Outer diameter of glass tube	$12.5\ cm$		

Table 2. Optical and thermal properties of the current state and the new state selective coatings of the studied PTSC absorber tube.

Selective Coating	Emissivity (ε)	Absorptivity (α)	Heat Resistance Temperature (K)
Deposited Black Chrome	0.15	0.92	**873 K**
Deposited Graphene Nanostructure	0.99	0.99	**1600 K**

Table 3. Mechanical and thermal properties of the current state and the new state glass cover materials.

	Coefficient of Linear Thermal Expansion	Maximum Operating Temperature	Knoob Hardness	Bending Strength	Impact Resistance
Pyrex	$3.3 \times 10^{-6}\ K^{-1}$	500 ℃ for short-term usage	480	$24\ MPa$	Depends on:[1]
BOROFLOAT 33	$3.25 \times 10^{-6}\ K^{-1}$	500 ℃ for short-term usage ($< 10\ h$) and 400 ℃ for long-term usage ($\geq 10\ h$)	480	$25\ MPa$	Depends on:[2]

[1] The way it is fitted, the size and the thickness of the panel, the type of impact involved, presence of drill holes and their arrangement as well as other parameters.
[2] The same factors as Pyrex impact resistance depends on.

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Table 4. The range of the wavelengths of UV, visible, and IR electromagnetic spectra.

Electromagnetic Spectrum			Wavelength Region
UV			290 nm – 400 nm
Visible			400 nm – 750 nm
IR	Reflected IR	NIR	750 nm – 1.4 µm
		SWIR	1.4 µm – 3 µm
	Thermal IR	MWIR	3 µm – 8 µm
		LWIR	8 µm – 15 µm
	FIR		15 µm – 1 mm

4. RESULTS AND DISCUSSION

Applying BOROFLOAT 33 and graphene nanostructure as the glass cover material and the absorber tube selective coating respectively leads to a lower radiative heat transfer between the glass cover and the sky, and also a higher radiative heat transfer between the absorber tube surface and the glass cover, which is in favor of PTSC thermal efficiency. In order to calculate the above-mentioned heat transfers, the surface temperatures of graphene coating and BOROFLOAT 33 glass cover are needed to be calculated. Since the specific heats of black chrome as the current state coating and graphene as the new state coating at the surface temperature of 489.1 K are respectively $509\ ^{J}/_{kg\ ℃}$ and $1150\ ^{J}/_{kg\ ℃}$ (Pop,Varshney, & Roy, 2012), assuming the mass of the coatings applied to the absorber tubes at the both states are the same, the surface temperature of graphene nanostructure coating would be calculated as 368.6 K. In addition, specific heats of Pyrex and BOROFLOAT 33 at the surface temperature of 320 K are respectively $840\ ^{J}/_{kg\ ℃}$ and $830\ ^{J}/_{kg\ ℃}$ (AG, BOROFLOAF 33-Thermal properties n.d.); therefore, the surface temperature of BOROFLOAT 33 would be calculated as 321 K. Having the surface temperatures of graphene and BOROFLOAT 33, the heat transfers mentioned above and consequently the thermal efficiency of the new state PTSC can be calculated according to equations (1) to (4), as shown in table 5.

Regarding the above-mentioned application, the thermal efficiency of the new state PTSC is calculated for three different forms of absorber tube internal enhancements. Finally in terms of thermal efficiency, regarding the fact that graphene nanostructure shows the highest emissivity and absorptivity of over 0.99, and the lowest reflectivity of less than 0.01 among all materials studied in before by scientists, over a wide range of electromagnetic wavelengths, from 400 nm to 2 μm, and also BOROFLOAT 33 has an excitation wavelength of 488 nm and consequently no fluorescence emissivity for the wavelengths shorter than 488 nm which means the lowest emissivity among all ones, and comparing the current state and the new state of the paper case study, it is observed how applying the new materials to the current state creates a new state accompanied with considerably rising thermal efficiency. Table 5 presents the numerical results of the two mentioned states. The results clearly show that with the application of graphene nanostructure material as the absorber tube coating and BOROFLOAT 33 as the glass cover material in the second-state absorber tube, the PTSC thermal efficiency significantly increased for the three forms of internal enhancements, compared with the efficiency achieved in the current-state absorber tube with the black chrome as the absorber tube coating and Pyrex as the glass cover material.

Table 5. Final results of the numerical and theoretical analysis between the current state and the new suggested state of the studied PTSC in terms of heat transfer and thermal efficiency.

	$q_{rad-a-g}$	$q_{conv-fluid}$			$q_{rad-g-sky}$	$q_{conv-g-air}$	$\eta_{Thermal}$		
		Twisted Tape Inserts	**Corrugated Tube**	**Internally Finned or Ribbed Tube**			**Twisted Tape Inserts**	**Corrugated Tube**	**Internally Finned or Ribbed Tube**
Current Status of Absorber Tube	397.52 W/m^2	276.895 W/m^2	184.75 W/m^2	485.76 W/m^2	162.52 W/m^2	28.63 W/m^2	0.58	0.46	0.59
Absorber Tube with New Materials	434.76 W/m^2	276.895 W/m^2	184.75 W/m^2	485.76 W/m^2	73.65 W/m^2	28.63 W/m^2	0.72	0.61	0.97

5. CONCLUSIONS

New materials application for the absorber tube selective coating and the glass cover of a PTSC unit have been proposed in order to optimize the thermal efficiency of a PTSC unit. Graphene nanostructure has been proposed as an ideal black coating for an absorber tube equipped with a vacuum glass cover. In addition, BOROFLOAT 33 has been suggested as an ideal glass cover material. Since the two materials proposed above to be used in solar thermal systems rendered ideal optical and mechanical properties, ideal thermal efficiencies have been achieved for the three enhanced absorber tubes which are absorber tube with twisted tape inserts, corrugated absorber tube, and internally finned or ribbed absorber tube, in comparison with the ones already achieved especially considering the author's previous work in this regard.

Nomenclature

A: Collector aperture area (m^2)
CVD: Chemical Vapor Deposition
G_s: Solar Irradiance (W/m^2)
$q_{conv-a-air}$: Heat from absorber tube to ambient air by convection (W)
$q_{conv-fluid}$: Heat from absorber tube to working fluid by convection (W)
$q_{conv-g-air}$: Heat from glass cover to ambient air by convection (W)
$q_{rad-a-g}$: Heat from absorber tube to glass cover by radiation (W)
$q_{rad-g-sky}$: Heat from glass cover to the sky (W)
q_{SolAbs}: Heat gain from sunlight (W)
$q_{ThermalLoss}$: PTSC thermal efficiency

$T_{g,s}$: Glass cover surface temperature (℃)
$T_{s,a}$: Absorber tube surface temperature (℃)
T_{sky}: The sky temperature
ε_a: Emissivity of absorber tube coating
ε_g= Emissivity of glass cover
σ: Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ W/_{m^2K^4}$)

Abbreviations

FIR: Far Infrared
IR: Infrared
LWIR: Long Wavelength Infrared
MWIR: Medium Wavelength Infrared
NIR: Near Infrared
SWIR: Short Wavelength Infrared
UV: Ultra Violet

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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