Effect of transparent conducting oxides on the temperature of the optical fiber cable

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Abstract:

The aim of this study is to show the effect of thin layers of transparent conducting oxides on the temperature of the glass fiber optic cable that transmits concentrated solar radiation using the center of the solar parabol,In this study we selected a thin layer of tin oxide and applied it on the surface of a fiberglass optical cable section, and this is done by determining the optical properties of the thin layer of tin oxide and the properties of the glass fiber optic cable, as well as the solar radiation taken on a specific day and hour in the wilaya of Ouargla from the city of Algeria.After setting the hypotheses and the mathematical model, we obtained equations that we programmed using the MATLAB program, and we obtained results that we analyzed and compared with previous theoretical results for the glass fiber cable without placing the thin layer of tin oxide.The obtained results showed that the surface temperature of the cable section has the lowest value at 750 nm wavelength of solar radiation and at a thickness of 1.13 **µm for the tin oxide thin layer.We also found that the surface temperature of the cable section using a thin layer of zinc oxide with a certain thickness at the surface of the cable section is lower than the temperature recorded at the surface of the cable section at the same thickness in the case of using a thin layer of tin oxide.In addition, the surface temperature of the cable section at a certain thickness in the case of using a thin layer of zinc oxide, which is inlaid, is lower than the temperature recorded at the surface of the cable section in the case of using a thin layer of pure zinc oxide at the same thickness.**

Keywords: Optical fibre, Transparent conducting oxides, Temperature, Transmittance, Wave length.

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1. Introduction

Since the concept of fiber optics entered the world of technology, it has recently attracted great attention for its use in applications such as fiber amplifiers and fiber lasers [1,2]this is because of its unique properties such as safety, electrical insulation, not being affected by the electromagnetic field, having a large bandwidth, light weight, and high sensitivity [3].The optical fiber material has been changed from silica glass to now include composite glass in order to meet the increasing demands for new optical devices that operate in different wavelength ranges.The manufacture of a coating of indium tin oxide (ITO) over optical fibers has been studied for the manufacture of optical fiber-based resonance refracts meters [4,5].In 2014 John Muth, LeandraBrickson, and others investigated the incorporation of vanadium oxide films into optical fibers for temperature sensing applications, this sensing mechanism depends on observing the shift in the spectrum, either in terms of a change in intensity at a specific wavelength or a shift at the edge of the band [6].In 2014 Wilfried Blanc and others, impregnated silica-based optical fibers with erbium-doped nanoparticles, and you may get optical fibers that have lower loss and improvements in the spectral properties of the fiber such as the shape and width of the gain curve and optical quantum efficiency [7].AritzOzcariz et al. studied how to develop a copper oxide thin film for a resonance-based optical fiber sensor in order to detect and quantify the loss [8]while Shaonian Ma, YanpingXu, and others studied fiber-optic sensors specialized in monitoring high temperatures [9].

On these studies, in this work we will apply a thin layer of transparent conducting oxide, for example tin oxide, on the surface of the glass fiber optic cable section,then we study the effect of this layer on the surface temperature of the cable section and compare it with the glass fiber optic cable without a thin layer, as well as the effect of the thickness of this layer on the change in the surface temperature of the cable section.

2. Mathematical Model

2.1. Concentrated Solar Radiation

2.1.1. Solar Radiation Reaching the Center Aperture

The total solar flux G_b that reaches the surface of the center of the solar parabola is given by the following relation:

$$Q_1 = G_b . A_a \tag{1}$$

Where:A_a The area of the center of the solar parabola, with$A_a = \pi.(D_a^2/4)$, $D_a$is represents the diameter of the solar collector.

2.2.2. Solar Radiation Reaching the Focus

Part of the Q_1 solar flux reaching the mirror is reflected by the mirror's reflectivity, so the amount of solar flux is:

$$Q_2 = \rho . G_b . A_a$$

(2)

This flow is then reduced by the observation factor F (Watching the receiver of the deterministic mirror as it relates to the angleθ_{max}) So we have Q_3.

$$Q_3 = F . \rho . G_b . A_a$$

(3)

Upon reaching the focus, we have Q_f.

$$Q_f = F . \rho . G_b . A_a . c_{max}$$

(4)

Where:ρ is the reflectivity of the aggregate surfac,F is viewing coefficient (watching the future of the peremptory mirror) and its phrase is given as follows [10]:

$$F = \frac{\sin^2\theta_{max} - \sin^2\emptyset_s}{4\tan^2\left(\frac{\theta_{max}}{2}\right)}$$

(5)

Where: θ_{max} is the angle that the incoming ray must enter at an angle equal to or less than it in order for the condition of total internal reflection to be achieved.

C_{max}isengineering focus, its expression is given as follows [11]:

$$C_{max} = \frac{A_a}{A_{bundle}} = \frac{\sin^2\theta_{max}\cos^2\left(\theta_{m0x} + 0.267° + \frac{\delta}{2}\right)}{\sin^2(0.267° + \frac{\delta}{2})}$$

(6)

Where:φ_s is shading angle (due to receiver size), $\frac{\delta}{2}$ is the error in measuring the angle of deviation of the reflective surface, $0.267°$ is half angle of incidence cone of solar radiation.

In this study, we consider that the hyperbolic center (the mirror) is ideal $\delta/2=0$, and we also consider the shading angle $\varphi_s=0$.

2.2.3. Incoming solar radiation to the cable

The solar radiation coming from the focal point is partially reflectedR, the material's reflection coefficient is called c_{max} (Tin oxide films).Accordingly, the incoming solar radiation to the cable Q_{inc} is given by the following statement:

$$Q_{inc} = F.\rho.G_b.A_{bundle}.c_{max}.(1 - R)$$

(7)

The reflectivity of the material (tin oxide thin films) is given as follows [12]:

$$R = \frac{(n-1)^2 + K^2}{(n+1)^2 + K^2}$$

(8)

Where: K is the inertia coefficient of the material (tin oxide thin films) and its relationship is given [13-16]:

$$K = \frac{\alpha.\lambda}{4.\pi}$$

(9)

Where:λ is the wavelength of the incident radiation, α is the absorption coefficient of the material (tin oxide thin films) and its relationship is given [17-20] :

$$\alpha = \frac{2.303.A}{d}$$

(10)

Where: d is membrane thickness, A is the absorbency of the material (tin oxide thin films) and its relationship is given [21]:

$$A = \log\left(\frac{1}{t}\right)$$

(11)

Where: t is optical transmittance.

2.2.4. Concentrated solar radiation entering the cable

The incoming solar radiation to the fiber optic cable, which is defined in the previous equation, is subject to another loss, which is represented by the loss through the pores.Accordingly, the solar radiation that enters the cable becomes related to it as follows:

$$Q_{in} = \rho.A_a.G_b.F.C_{max}.(1 - R).\varphi_{pf}$$

(12)

2.2.5. Mathematical model

Figure 1 shows the proposed model in the study

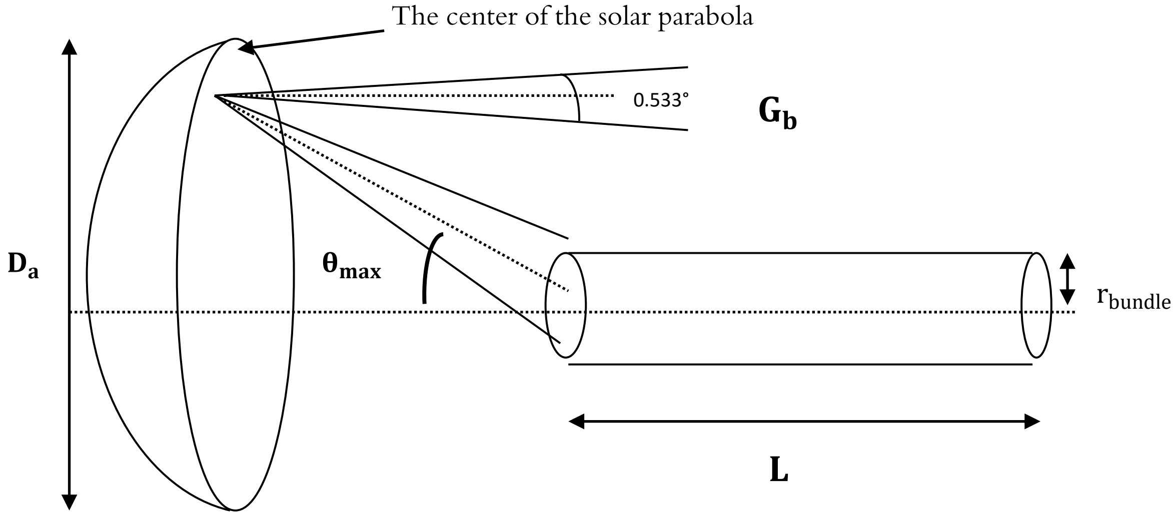


Figure 1.Mating of the solar parabolic center and the fiber optic cable.

Hypotheses:In our study, we take into account the following hypotheses:

- ✓ Temperature change along the optical fiber only.
- ✓ We apply a thin layer of tin oxide to the surface of the cable section
- ✓ Convection losses on the front section surface and the side surface of the cable.
- ✓ The study is limited to wavelengths in the visual field.
- ✓ The change in temperature with respect to time is negligible.
- ✓ The cable is considered to consist of a homogeneous group of optical fibers.
- ✓ Power transmission systems via fiber optics do not store energy.
- ✓ Energy losses from a parabolic solar collector are negligible.
- ✓ The solar radiation is positioned in a direction perpendicular to the aperture of the parabolic solar collector.
- ✓ The reflectivity of the material making the parabolic solar collector is high.
- ✓ There is no error in tracking the sun.

2.2.6. Differential equation for temperature along the fiber optic cable

We have the energy equation for an optical fiber bundle as follows:

$$Q_x = Q_{x+dx} + Q_{con-sid} \quad (13)$$

Using Taylor's posting:

$$Q_x = Q_x + \frac{dQ_x}{dx}dx + Q_{con-sid}$$

(14)

Where:Q_x is Conductive heat transfer is given as:

$$Q_x = -K_{eff}\pi r_{bundle}^2 \frac{dT}{dX}$$

(15)

Substituting Q_x and $Q_{(con\text{-}sid)}$ into the previous equation, we find:

$$\frac{d(-K_{eff}\pi r_{bundle}^2 \frac{dT}{dX})}{dX}dX + 2\pi r_{bundle} h_{con-sid} dX(T - T_a) = 0$$

(16)

Simplifying the last relation, we get:

$$\frac{d^2T}{dX^2} - m^2T = -m^2T_a$$

(17)

Where:$m^2 = \frac{2h_{con-sid}}{r_{bundle} \cdot K_{eff}}$

* **Solve the differential equation**

Equation (17) has the solution in the following form:

$$T(X) = C_1 \exp(mX) + C_2 \exp(-mX) + T_a$$

(18)

Boundary Conditions:

3. The first condition is when X = 0, the incoming radiative flux on the pore material leads to convection, so the incident heat flux is related to the porosity (φ_{pore}).
4. The absorbed flow is transported by conduction in the bundle or by convection to the air at the surface of the front section [22].

$$Q_{inc} \cdot \varphi_{pore} = -K_{eff}\frac{dT}{dx}|_{x=0} + h_{con-in}(T_{X=0} - T_a)$$

(19)

Where: T is temperature gradient along the cable.

After making several substitutions and steps, we finally get the following final equation:

$$Q_{inc} \cdot \varphi_{pore} = C_1(-K_{eff}m + h_{con-in}) + C_2(K_{eff}m + h_{con-in})$$

(20)

The second condition: X = L

$$T_{X=L} = T_L = T_a$$

(21)

$$T_L = C_1 \exp(mL) + C_2 \exp(-mL) + T_a$$

(22)

$$C_1 \exp(mL) + C_2 \exp(-mL) = 0$$

(23)

And from him:

$$C_1 = -C_2 \frac{\exp(-mL)}{\exp(mL)}$$

(24)

After making several substitutions and shortcuts, we find:

$$T(X) = \frac{Q_{inc} \cdot \varphi_{pore}\left(-\frac{\exp(-mL)}{\exp(mL)} \exp(mX) + \exp(-mX)\right)}{\left(K_{eff} m\left(\frac{\exp(-mL)}{\exp(mL)} + 1\right) + h_{con-in}\left(1 - \frac{\exp(-mL)}{\exp(mL)}\right)\right)} + T_a$$

(25)

2.2.7. Factors affecting the surface temperature of a fiber optic cable section

The surface temperature of a fiber optic cable section is affected by several factors, including:

* The surface temperature of a fiber optic cable section is related to the concentrated solar radiation entering the cable.
* The surface temperature of a fiber optic cable section is related to the wavelength of solar radiation.
* The relationship of the surface temperature of the fiber optic cable section to the thickness of the thin layer of the transparent conducting oxides is as follows:
* The relationship of section surface temperature in terms of permeability.
* The effect of transmissive and reflected intensity.

3. Results and discussion

3.1. Factors affecting section surface temperature

3.1.1. The effect of wavelength on temperature

Figure 2 represents the temperature changes along the length of the fiber optic cable; a thin layer of tin oxide is deposited at the surface of a fiber optic cable cross section, we notice through the curve that the temperature is high at the entrance of the cable and gradually decreases along the length of the cable until it stabilizes at the temperature of the air surrounding the cable.We explain the high temperature rise at the entrance of the cable to the fact that some radiation frequencies are absorbed in the first part of the cable and heat it up, this part of the cable acts as a frequency filter[23] and the decrease in temperature along the length of the cable is due to the attenuation, which increases with the length of the cable.We also note that the temperature of the cable at wavelength 550nm is higher than its temperature at wavelength 650nm, and the latter has a higher value than its temperature at the wavelength of 750 nm, and we explain this to the high absorption coefficient at the wavelength of 550 nm due to the presence of -OH ions, and this is what makes the temperature at the surface of the cable section high. The absorption coefficient decreases in the visible and near-infrared range and has the lowest value at the wavelength of 750 nm [24]this makes the temperature low at the wavelength of 750nm.

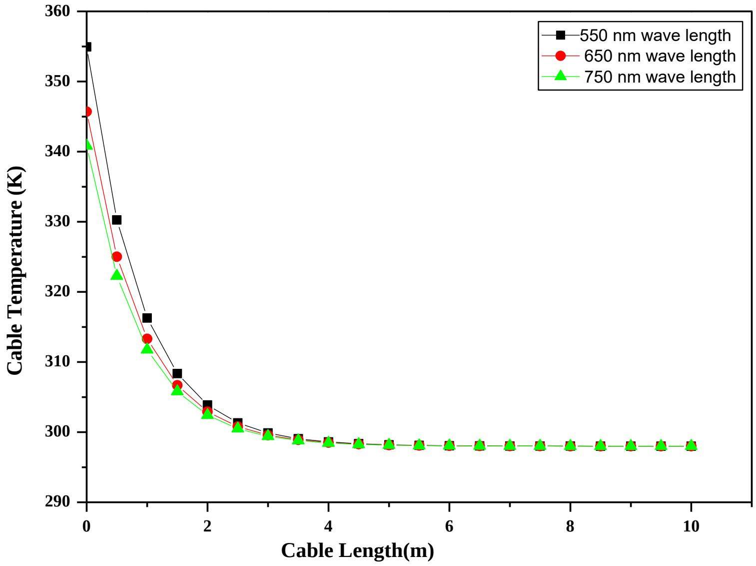


Figure 2.Temperature changes in terms of wavelength.

When comparing the curves in Figure 3, for the temperature change along the optical fiber cable in the case of applying a thin layer of tin oxide (our work) with a previous theoretical study of an optical fiber without laying a thin layer,we note that the temperature recorded along the cable in the case of puting a thin layer of tin oxide is much lower compared to the temperature recorded along the fiber optic cable without placing the thin layer.The reason for this is that tin oxide is a transparent conducting oxide that has a light transmittance and a weak absorption coefficient, and this is what makes the temperature low.

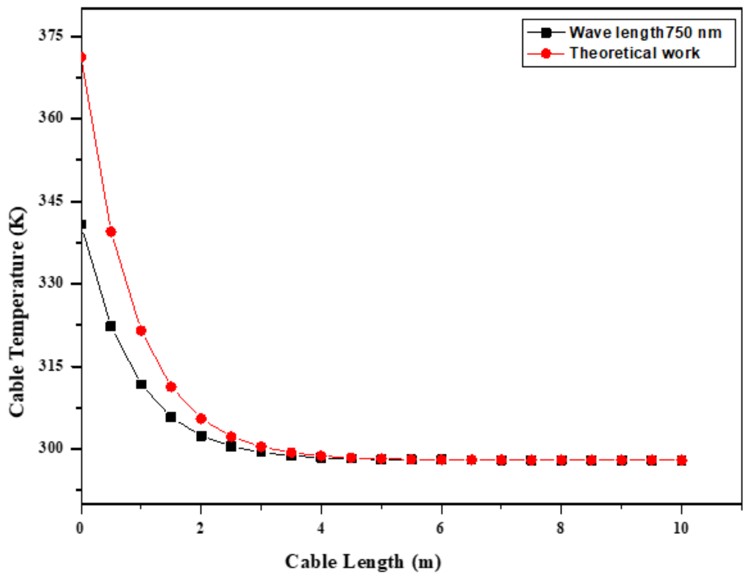


Figure3 .Temperature change along the fiber optic cable as a thin layer of tin oxide is deposited at the surface of the cable section.

3.1.2. The change in the surface temperature of the cable section as a function of total solar radiation

Figure 4 represents the changes in the surface temperature of the cross section in terms of total solar radiation for different wavelengths, we note that the higher the solar radiation, the higher the surface temperature of the cable section, we also note that the temperature recorded at the surface of the section at wavelength 750 nm is lower than the temperature recorded at the surface of the section at wavelength 650 nm.

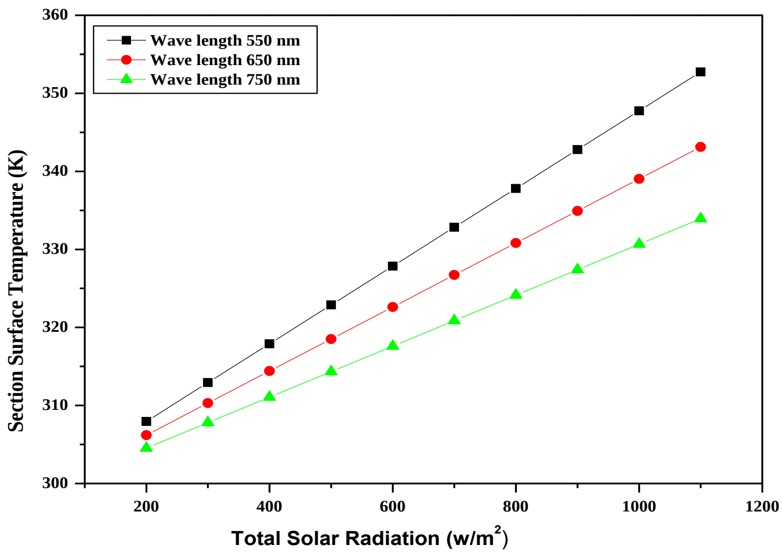


Figure 4.Change in the surface temperature of the fiber optic cable section in terms of the total solar radiation entering the cable with the application of a thin layer of tin oxide on the surface of the cable section.

This last recorded result is lower than the surface temperature of the section at wavelength 550 nm, this is at the same value as the total solar radiation, and the reason for this is that the absorption coefficient is high at the wavelength of 550 nm, and it decreases with increasing wavelength.Increasing the absorption coefficient, in turn, leads to an increase in the damping coefficient, according to the relationship between them.

When comparing the surface temperature Figure 5 of the section at a wavelength of 750 nm, in the case of a thin layer of tin oxide at the cable entrance with the reference curve (optical fiber without tin oxide film), we note that at the same value of total solar radiation, the surface temperature of the cable section in the presence of a thin layer of tin oxide is lower than the temperature recorded on the surface of the cable section without the presence of this layer.The reason for this is due to tin oxide, which is one of the transparent light-transmitting oxides, which has a high transmittance to light and a weak absorption coefficient, which is the reason for lowering the temperature at the surface of the section of the cable.

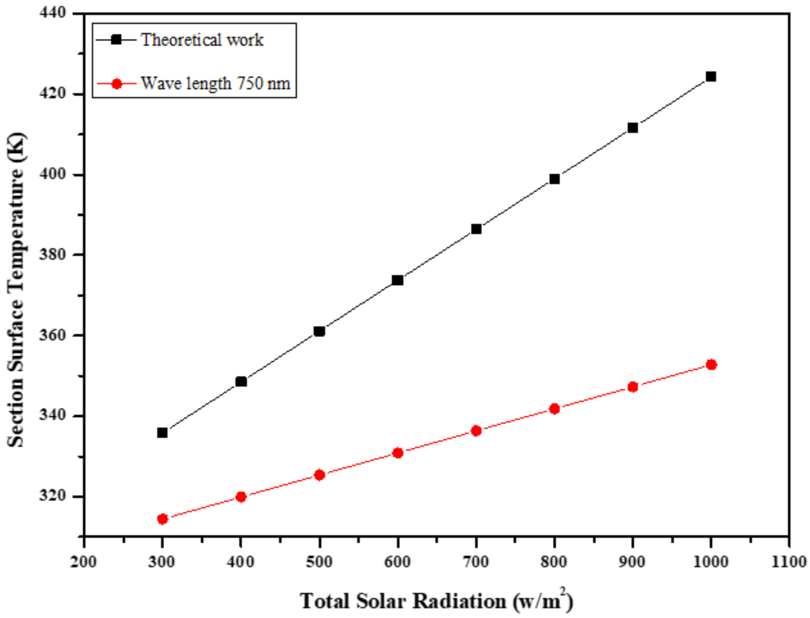


Figure 5. The temperature change of the surface of the fiber optic cable section in terms the total solar radiation entering the cable at a specific wavelength with put a thin layer of tin oxide at the surface of the cable section.

3.2.Thickness effect

The surface temperature of the section as a function of wavelength

Figure 6 represents the surface temperature changes of the section as a function of wavelength, we can see from the figure that as the wavelength increases, the surface temperature of the section decreases, the reason for this is that the absorption coefficient is highest at wavelength 0.55 µm, and then decreases with increasing wavelength in the visible field.We also notice from the figure that the surface temperature of the section at a thickness of 0.76 µm is greater than the temperature recorded for the surface of the section at a thickness value of 0.93 µm, and the latter is greater than the temperature recorded for the surface of section at a thickness of 1.13 µm.

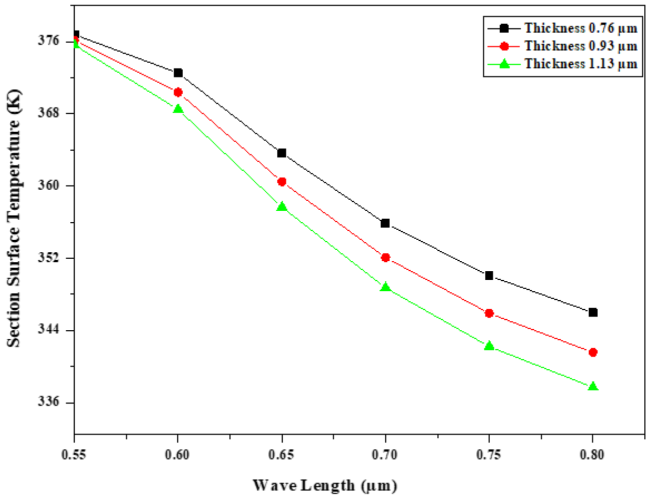


Figure 6. Change of surface temperature of the fiber optic cable section in terms of wavelength with the application of a thin layer of tin oxide at the surface of the cable section.

Comparing the surface temperature curve of a cable section in terms of wave length at a thickness of 1.13 µm for the tin oxide layer laid on its section surface with the theoretical work (surface temperature curve of a fiber optic cable section without the presence of the tin oxide layer) in Figure 7,we note that at the same value of wavelength, the surface temperature of the cable section at a thickness of 1.13µm is lower than the surface temperature of the reference cable section, this is because tin oxide has a high transmittance to light, that is, the absorption coefficient is weak, and therefore the surface temperature of the section is low compared to the surface temperature of the reference cable section.

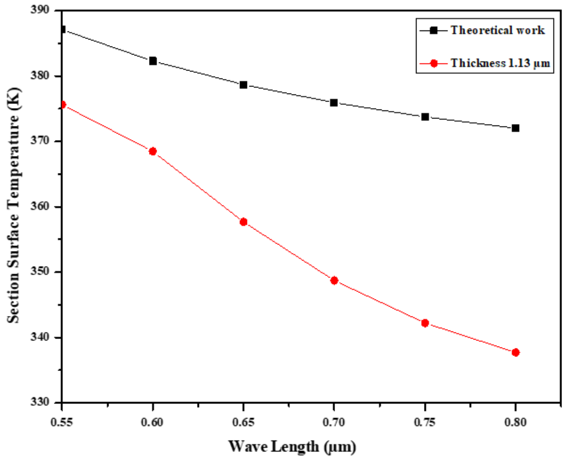


Figure 7. Change in the surface temperature of the fiber optic cable section in terms of wavelength with the application of a thin layer of tin oxide at the surface of the cable section of a specified thickness.

The surface temperature of the cable section as a function of total solar radiation

Figure8 represents the changes in the surface temperature of the section in terms of total solar radiation with variable values of the tin oxide layer placed at the entrance of the fiber optic cable. We notice from the figure that the greater the total solar radiation, the higher the surface temperature of the fiber-optic cable section, we also note that the surface temperature of the cable section at a thickness of 1.13μm is lower than the temperature recorded in the case of a thickness of 0.93μm, and the latter is lower than the temperature at a thickness of 0.76μm, and that at the same value of total solar radiation. The reason for this is that there is an inverse relationship between temperature and thickness.
This idea has been confirmed in previous work[25].

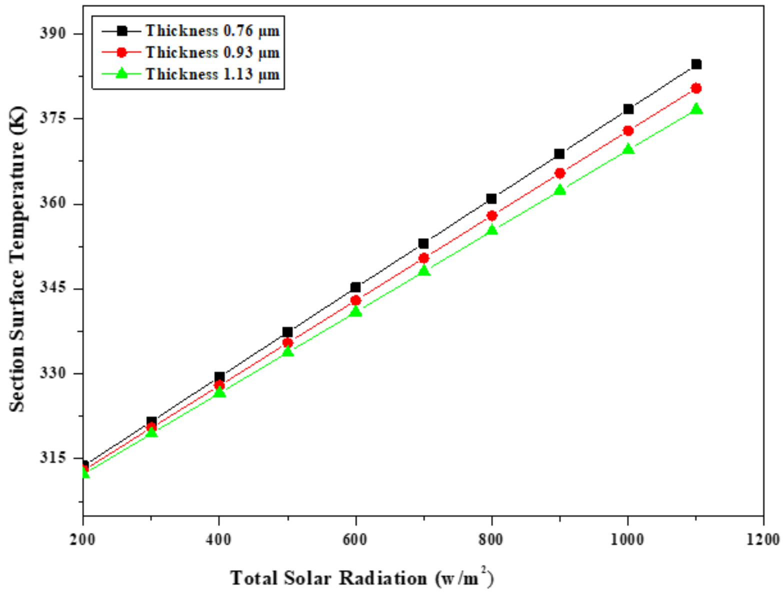


Figure 8. Temperature changes of the surface of the fiber optic cable section in terms of the total solar radiation entering the cable by placing a thin layer of tin oxide on the surface of the cable section of variable thickness.

Material effect

Figure 9 represents temperature changes along the length of a fiber optic cable, we note from the curve that the temperature is high at the entrance of the cable and decreases gradually along the length of the cable, until it reaches the same temperature as the air surrounding the cable, and the reason is as mentioned previously, as we notice at the entrance of the cable, the temperature of the optical fiber cable that contains a thin layer of zinc oxide (ZnO) is lower than the temperature of the optical fiber cable that does not contain a thin layer of tin oxide (SnO_2), the reason for this is that zinc oxide has a higher transmittance to light than that of tin oxide. This is because zinc oxide, when exposed to hydrogen plasma, is more stable than tin oxide, whose optical transmission is deteriorated by this plasma [26,27].

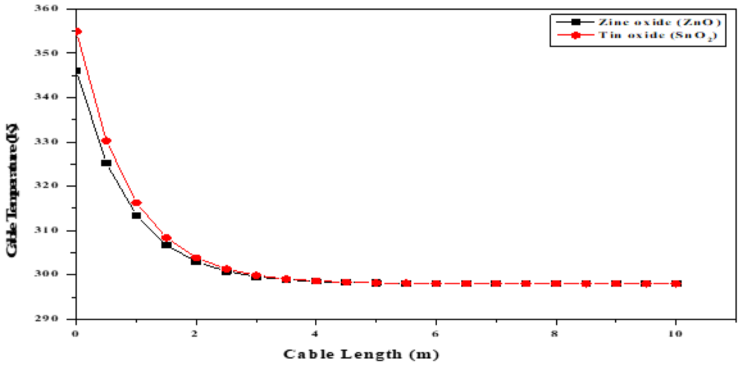


Figure 9.Temperature change along the fiber optic cable with the application of tin oxide (SnO_2) and zinc oxide (ZnO) at the surface of the cable section.

3.2.1. The surface temperature of the section in terms of total solar radiation

Figure 10 represents the changes in the surface temperature of the section in terms of the total solar radiation of the fiber optic cable, We notice from the figure that the higher the value of solar radiation, the higher the temperature of the surface of the section, and we also note that in the case of the same value of total solar radiation, the surface temperature of the fiber optic cable section that contains a thin layer of zinc oxide is less than the surface temperature of its section in the case of It contained a thin layer of tin oxide, the reason for this is that zinc oxide has a high transmittance to light compared to that of tin oxide.

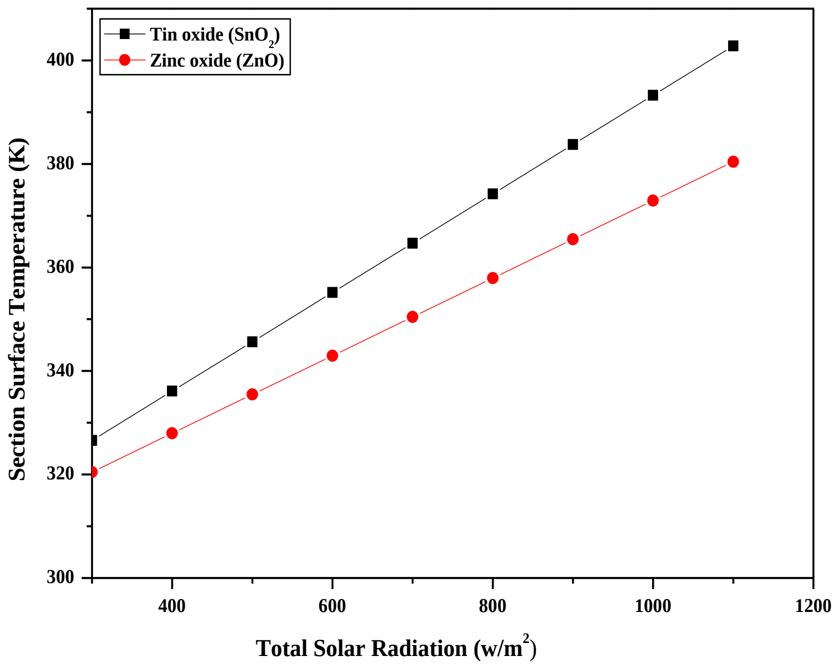


Figure 10. Change in the surface temperature of the fiber optic cable section in terms of total solar radiation with put of a thin layer of tin oxide (SnO_2) and zinc oxide (ZnO) at the surface of the cable section.

3.3. Dopingeffect

We notice from the Figure 11 that the temperature is high at the cable entrance and gradually decreases until it reaches the same temperature as the air surrounding the cable, we also notice at the entrance of the cable that the temperature of the fiber optic cable that contains a thin layer of nickel oxide doped with copper 1% is lower than the temperature recorded for the fiber optic cable that contains a thin layer of pure nickel oxide, the reason is that the permeability of nickel oxide increases with the increase in the percentage of grafting with it, this is due to the presence of a decrease in the absorption of visible light energy, i.e. a decrease in the number of electronic transitions between band conduction and band valence.

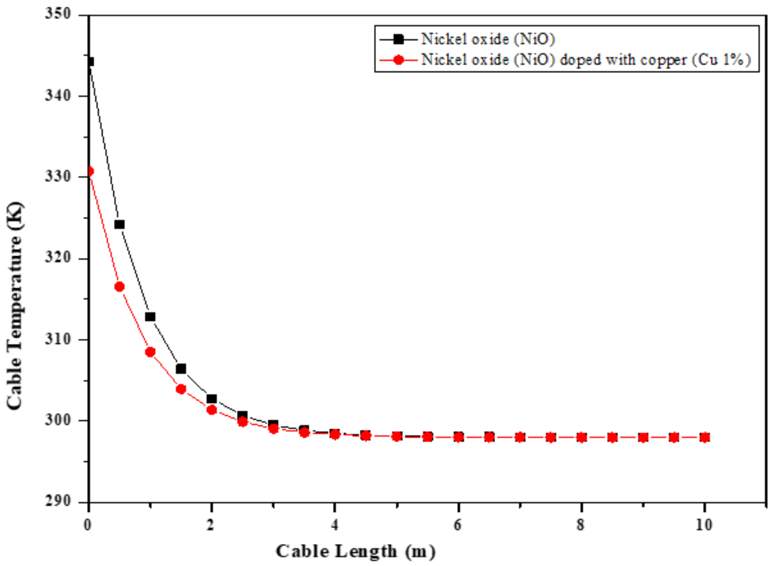


Figure 11.Temperature change along the fiber optic cable with put thin layer of pure (NiO) and nickel oxide doped with copper (Cu 1%).

The curve represented in Figure 12 represents changes in temperature along the optical fiber cable with a thin layer of zinc oxide (ZnO)puted on the surface of its section, we note from the figure that the temperature is high at the entrance of the cable, then it gradually decreases until it reaches the ambient air temperature with the cable, we also note that at the entrance of the cable the temperature of the optical fiber cable containing a thin layer of zinc oxide doped with nickel (Ni 10%) on the section surface it is lower than the temperature of the optical fiber cable containing a thin layer of zinc oxide not doped. The reason for this is that zinc oxide increases its transmittance rate by increasing doping rates, and the reason for this is the decrease in the absorption of visible light energy, that is, a decrease in the number of electronic transitions between the conduction and valence bands.

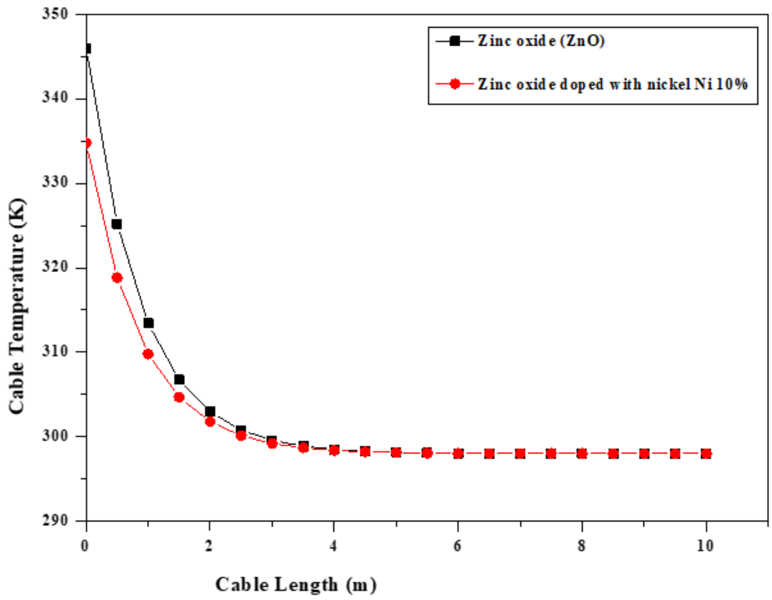


Figure 12. Temperature change along the fiber optic cable with put a thin layer of pure zinc oxide (ZnO) and zinc oxide doped with nickel (Ni10%) at the surface of the cable section.

3.4. Transmittance Effect

The Figure 13 represents the changes in the surface temperature of the section in terms of the transmittance intensity,we notice from the figure that in the visible field, as the transmittance increases, the surface temperature of the section decreases, the reason for this is that the light transmittance of transparent conducting oxides increases with increasing wavelength in the visible range, thus the surface temperature of the section decreases with increasing wavelength in the visible field.

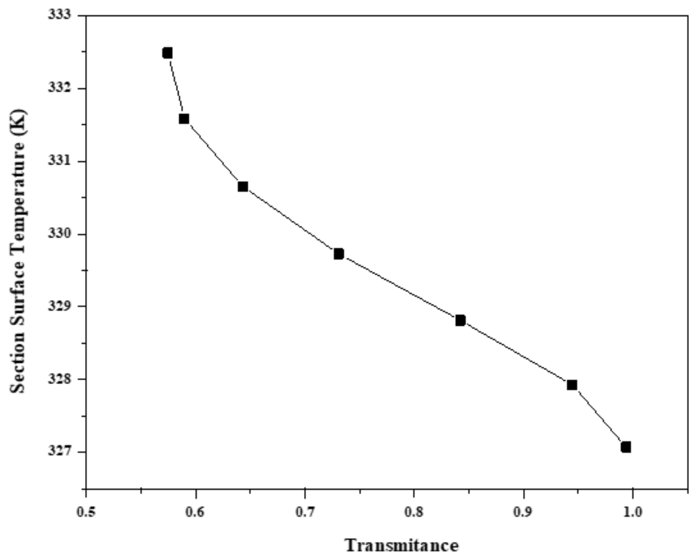
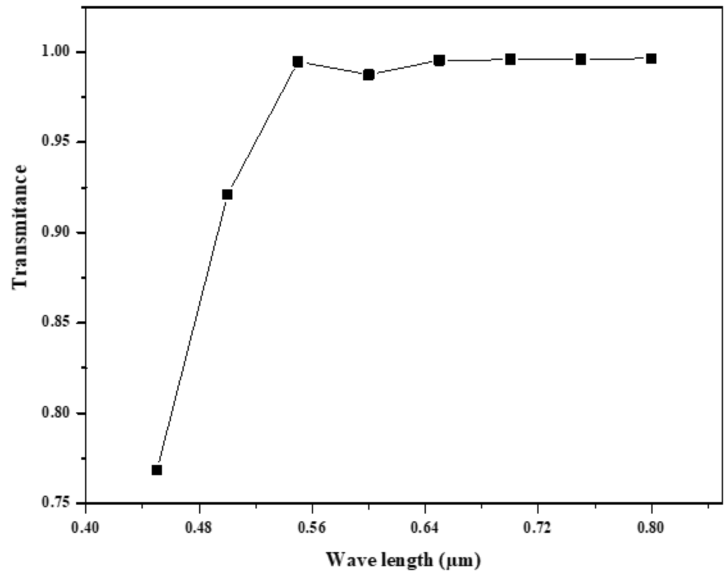


Figure 13. Change in section surface temperature in terms of transmittance.

Figure 14 shows the changes of transmittance in terms of the wavelength of radiation, as it is generally observed that with increasing wavelength of radiation the transmittance increases, and the increase in transmittance is accelerated in the wavelength (0.45-0.56) μm, after that, it will stabilize almost at the value 0.96whatever the wavelength change, it is consistent with what was stated in the work [28].



14. Transmittance changes in terms of wave length.

4. Conclusion

When placing a thin layer of tin oxide on the surface of the fiber optic cable section and studying the effect of this layer on the temperature of the cable, we obtained the following results:

✓ The temperature at the entrance of the glass fiber optic cable is high and gradually decreases along the cable, within a certain thickness of the tin oxide layer, the temperature along the cable at wave length 750 nm is lower than the temperature along the cable at wave length 650 nm, this latter is lower than the temperature along the cable at wave length 550 nm.

✓ At a specified value of the thickness of the tin layer placed at the surface of the fiber optic cable section, and exactly at the wave length 750 nm, the temperature along the cable is lower than the temperature along the length of the optical fiber cable in the case of not placing the tin oxide layer.

✓ The surface temperature of the fiber optic cable section increases with the increase in the total incident solar radiation, At a certain thickness of the tin oxide layer and a specific value of the total incident solar radiation, the surface temperature of the cable section at 750 nm wave length is lower than the surface temperature of the cable section at 650 nm wave length, in turn, this last result is lower than the temperature recorded for the surface of the cable section at 550 nm wave length.

✓ For the same amount of incident solar radiation, the surface temperature of the fiber optic cable section at 750 nm wave length with a specific thickness of the tin oxide layer is less than the surface temperature of the glass fiber optic cable section without the presence of this layer.

✓ For the same amount of solar radiation, and at a specific amount for the wave length of the visible field, the surface temperature of the cable section with a thickness of 1.13 µm for the tin oxide layer is less than the surface temperature of the cable section with a thickness of 0.93 µm, and the latter is less than the surface temperature of the cable section with a thickness of 0.76 µm.

✓ At the same amount of incident solar radiation, and for a specific value of wave length in the visible field, the surface temperature of the cable section at a thickness of 1.13µm for the tin oxide layer is lower than the surface temperature of the cable section without the presence of this layer.

✓ For the same amount of incident solar radiation, the surface temperature of the cable section at a specified thickness of the zinc oxide layer is less than the surface temperature of this section at the same thickness of the tin oxide layer.

✓ The temperature recorded along the length of the glass fiber optic cable with a specific thickness of the nickel-doped zinc oxide layer is 10% lower than the temperature recorded along the glass fiber optic cable with the same thickness of the pure zinc oxide layer.

✓ The surface temperature of a fiber optic cable section decreases with increasing light transmittance, and light transmittance increases with increasing wavelength in the visible range.

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