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Characterization of thermal losses in an evacuated tubular solar collector prototype for medium temperature applications

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Abstract

Design, construction and characterization of an evacuated 1.3 m long, tubular solar collector are presented. The collector is open at both ends for input and output of the fluid to be heated, and at one end a commercial, stainless steel bellows is soldered at the metal-glass seal, which allows for the higher thermal expansion coefficient of the steel tube as compared to the glass jacket. A selective coating of Ni/NiOwas electrochemically deposited on the stainless steel tubecollector using a two-step process. Collector losses are characterized up to 200 ^{o}C as a function of pressure in the space between the borosilicate glass and the stainless steel tube. A16-channel thermocouple system was used to characterize the dynamic thermal behavior of the collector. The suppression of convection as a heat transport mechanism in the vacuum zone is demonstrated for a pressure of 10^{-4}Torr. The absorption characteristics of the collector were studied by placing it outside on a sunny day. A critical analysis of the possibilities of using thesolar collector in food industry is presented.

Keywords: Solar-thermal collectors; selective coatings; Ni/NiO; bellows seal.

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1. Introduction.

The best known tubular solar collector receivers with an inner steel tube, with two open ends for the inlet and outlet of the medium to be heated, are those used in solar thermal plants for electricity generation[1]. The technology of glass to metal seals of these collectors (2 to 4 meters long) is complex, because it requires the selection of materials to match the different linear thermal expansion coefficients of borosilicate glass and the metal counterpart.Usually,a system based on bellowss is utilized to allow for the relative large thermal expansion coefficient of the steel pipe of the collector, often in combinationwith gas adsorbing substances (getters) in order to maintain the vacuum for many years [2]. There are many promising applications for solar collectors at low and medium temperatures, for instance, for heating of water for domestic applications [3], solar cooking systems [4], industrial processes like sterilization, pasteurization, drying, hydrolysis, distillation and evaporation, washing and cleaning, and polymerization[5]. A typical example involves the preparation of fried snacks; the food industry uses a large amount of edible oil, which is typically heated using natural gas or diesel fuel to a temperature of 150-170 ^oC. This results in large annual expenses and CO_2 emissions. All-glass evacuated collectors are not suitable for this application, due to the high pressures that can develop, so the use of collectors with inner tube of stainless steel is an attractive option. The present work is aimed at the development of a prototype of a tubular vacuum-insulated stainless steel core collector with an efficiency of approximately 50% at 150 ^oC suitable for food processing in industrial applications. The prototype is somewhat smaller, about one meter long, and technologically more accessible than those used in power generation plants. The selective coating on the stainless steel tubes was prepared using an electrochemical method for deposition of Ni/NiO[6]. The assembly of the collector also involved the development of glass to metal seals in order to maintain a stable vacuum.

2. Collector design

The collector design involves a stainless steel tube as the fluid driver (approximately 19/17 mm outside/inside diameter) with inlet and outlet. The stainless steel tube is coated with a Ni/NiO selective coating prepared using an electrochemical method that is described in the next section. In terms of its design, the prototype collector is similar to the prototype reported in literature [7]. This collector uses bellowss on only one end, which simplifies its manufacture; for the prototype collector we introduce several innovations in the process of preparing the seals. Figure (1) presents a picture of the collector prototype. A borosilicate glass tube providing excellent light transmission is used to achieve vacuum isolation of the stainless steel tube with the selective coating. At both ends of the glass tube, flat ground glass extensions are prepared in order to provide a good seal with the stainless steel tube (see figure 1).The seals are achieved by using an epoxy resin, which does not suffer any important transformations up to 70 ^0C. In order to avoid heating of the epoxy resin, the seals are designed to reduce transmission of heat to the glass-metal contact area. One of the seals has an adapted welded vacuum bellowss (Kurt J. Lesker Co.) which allows for the thermal expansion of the steel collector tube. At 150 °C the expansion is almost 1 mm, which would cause a rupture of the glass - metal seals. For collectors with parabolic mirrors, the glass-metal seals are made by heating and interdiffusion at both sides, and using an alloy (Kovar) whose thermal expansion coefficient is similar to that of borosilicate [2]. The stainless steel seals of the prototype collector are welded (electric welding with argon) to a stainless steel tube manifold, which was designed to allow for cooling of the seals during welding in order to prevent deterioration of the epoxy resin. The vacuum in the borosilicate glass tube was achieved using a small valve welded to the seal containing the bellowss. The vacuum was attained using a turbomolecular pump (AdixenDrytel 1025). The quality of the seals appears to be adequate, since the pump achieved a high vacuum level without any problem and, upon turning off the pump; the pressure gauge indicated that the vacuum is essentially the same one day after evacuation. For collector testing at longer times, a barium getter could be employed to maintain the vacuum.

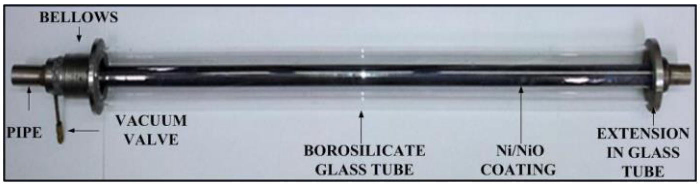

Fig.1. Picture of the collector prototype; the parts are labeled.

3. Experimental

The selective coating on the surface of the stainless steel tube was deposited with electrochemical methods in a cylindrical cell and employing nickel-based baths.The cell was designed to accommodate the collector tube. A programmable high power supply (Agilent, model U8002A) was used to provide the necessary electric current and an aluminum mesh was used as counter electrode. The stainless steel tube surface was polished first with sandpaper with an increasingly finer finish, and finally with alumina slurry. After polishing the tubes, they were treated with ethanol, acetone and concentratedNaOH. Platinum gauze was employed as counter electrode and the reference electrode was Ag/AgCl.The reflectance spectra in the solar radiation range of the selective coatings was obtained using a spectrophotometer (AVANTES, model AVASpec 2048, Wavelength range: 200-1100 nm), a light source (AVANTES,AvaLight-DH-S-BAL Balanced Deuterium-Halogen Light Source, Wide spectrum: 200-2500 nm)and an integrating sphere (Ocean Optics, model ISP-50-8-R-GT,Spectral range: 200 to 2500 nm). On the other hand, reflectance spectra in the NIR/MIR regions were obtained with anInfrared (FTIR & IR) spectrometer (Perkin Elmer, model Frontier NIR/MIR, Spectral range: 2 to 20 μm) with an integrating sphere (Spectral range:2 to 15 μm). In order to characterize the heat loss of the tubecollector, a spiral of resistive wire spanning the entire length was inserted in the interior of the collector stainless steel tube [1]. This resistive wire spiral simulates a condition of hot fluid flow. The resistive wire was connected to a programmable high power supply (Agilent, model U8002A); the electrical circuit can dissipate power up to 75 W. A 16-channel thermocouple monitor (Stanford Research, model SR630) was used to measure the temperature at different locations of the collector. In figure (2), the locations where the thermocouples were placed are shown. An electrical current was applied to heat the tube for about 50 minutes in order to reach the equilibrium temperature.When equilibrium isreachedthe temperature changes were in the order of$\pm 1^{o}$C.

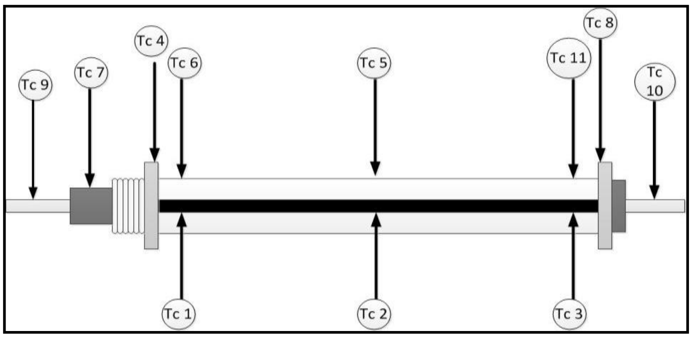

Fig.2. Location of the thermocouples for the determination of the temperature of the stainless steel and glass parts of the collector.

5. Experimental Results

5.1 Selective coatings.

Solar absorptance and thermal emittance werecalculated for a spectral distribution of terrestrial beam normal radiation at Air Mass 1.5 with the next relations[8]:

$$\alpha_s = 1 - \frac{1}{n}\sum_{j=1}^{n}\rho_j \qquad (1a)$$

$$\varepsilon_s = 1 - \frac{1}{n}\sum_{j=1}^{n}\rho_j \qquad (1b)$$

Where α_s,ρ_s and ε_s,are the solar absorptance, reflectance and thermal emittance,respectively.In figure (3) we show the reflectance spectra in solar radiation range of the electrochemically deposited Ni/NiO coating on stainless steel substrates: the solar absorptance value was (96± 2) %, whichindicates that the coating has excellent solar spectrum absorbance.

In figure (4) we show the infrared reflectance spectra:the thermal emittance value was (19 ±0.4) %.LiraCantú et al. [6] reported that for very high values of the solar absorptance, the thermal emittanceis affected negatively due to a non-optimized thickness of the NiO layer. A thick NiOlayer is very good for solar absorptance performance, but increases thermal emittance, negating the advantage of the high thermal reflectance of the nickel layer.

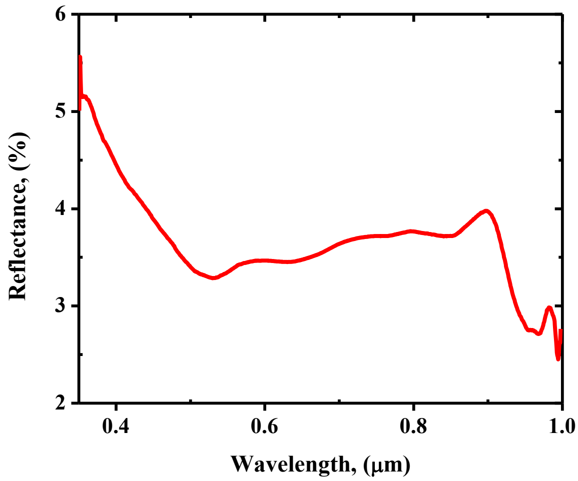

Fig.3. Reflectance spectra in solar radiation rangeof coating based on Ni/NiOdeposited stainless steel substrate.

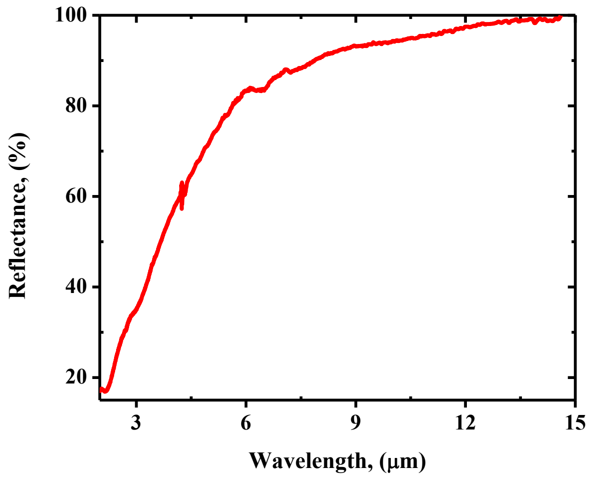

Fig.4. Infrared reflectance spectra of coating based on Ni/NiOdeposited stainless steel substrate.

5.2 Characterization of heat losses.

Heat losses in parabolic receivers have been studied in detail recently[9,10]. Heat transfer mechanisms in the space between the stainless steel tube and the glass are determined by the pressure of the gas in that space. The conduction-convection power loss, P_c (W), of this mechanism can be described in general by the next equation:

$$P_c = hA(T - T_a) \tag{2}$$

Where h($Wm^{-2}K^{-1}$) is the heat transfer coefficient, T and T_a(K) are the absolute temperature of the hot surface and ambient temperature,respectively,and A is the area (m^2) of metal surface at temperature T.
At a pressure of 10^{-4}Torr,the heat transfer coefficient (h)is reduced to a considerable extent. The loss mechanism by thermal radiation can be analyzed in terms of the Stephan-Boltzmann law, which describes the power loss due to thermal radiationP_r(W) of a surface at absolute temperature (T):

$$P_r = \varepsilon\ \sigma\ AT^4 \tag{3}$$

Where σ is the Stephan-Boltzmann constant ($5.67x10^{-8}$ $Wm^{-2}K^{-4}$), A(m^2) is the radiating surface area and ε is the emissivity of the surface area. In this case,the inwardthermalradiation of borosilicatetubeshould be taken intoconsideration, which requires a thorough knowledge of the infrared emissivity of the tube surfaces, which makes the use oftheoreticalequations to calculate the radiation powerintwo concentric cylindersconfiguration somewhatcomplicating. Among the collectors heat losses, conduction and convection are function of the temperature difference between the absorber temperature and ambient temperature ($T - T_a$), and radiation is a function of fourth–power absolute absorber temperature difference ($T^4 - T_a^4$). Three similar relations are widely used to describe the collectors total lossesP_L(W/m)[11]:

$$P_L(W/m) = \xi T + \beta T^4 \qquad \text{(With } T \text{ in } ^0\text{C)} \qquad (4)$$

$$P_L(W/m) = \xi T + \beta T^4 \qquad \text{(With } T \text{ in K)} \qquad (5)$$

$$P_L(W/m) = \xi \Delta T + \beta \Delta T^4 \qquad \text{(With } T \text{ in K)} \qquad (6)$$

In these relations the values of ξ and β are computed with Matlab software from experimental points.In figure (7) we show the total specific power loss $P_L$of the prototype collector, where temperature T_2(°C) was measured in the center of the stainless steel tube (figure 2) at atmospheric pressure and at 2.2 x 10^{-4}Torr. In figure (7) it is clearly shown that when the inside of the glass sleeve is at atmospheric pressure, the total specific power loss $P_L$has a linear dependence on temperature in practically the entire range of T_2as predicted in equation (2). In this case, the total specific power loss mechanism is determined by air conduction - convection. Under high vacuumconditions, the linearityof the $P_L$versus T curve is lost, indicating the suppression of the conduction-convection mechanism given by equation (2).

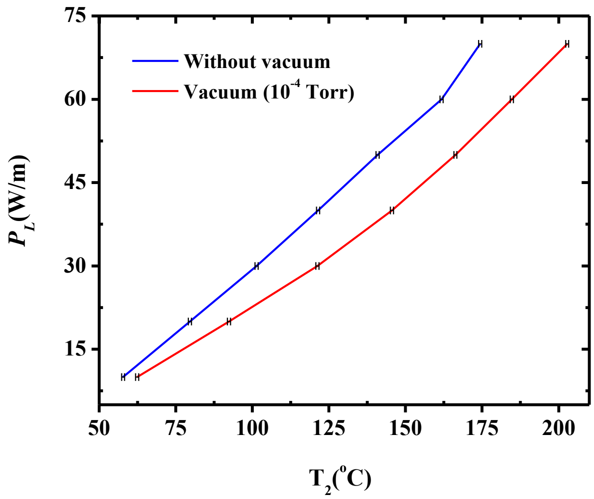

Fig.7. Specific power loss in function of temperature of the prototype collector with a heating power of 75 W, with and without vacuum in the space between absorber collector and glass

The heating of the glass tube when the steel tube temperature is rising is shown in figure (8), illustrating the relationship between the glass outside temperature (T_5) and the temperature at the middle of the stainless steel pipe (T_2). The measurements were performed with vacuum and without vacuum. The radiate character of this heating is clearly shown by the non-linear dependence in the vacuum case. This experimental data also show the absence orsuppression of the conductive mechanism in the presence of air at atmospheric pressure inside of glass tube.

Measurements of the collector temperature gradient along the metal tube, in conditions of vacuum and without vacuum, show a jump inthe collector temperaturewhen moving fromthe outside to the inside of the glass tube zone.This is logicallylinkedtoconvectioninthe metallic zones of the collector outside of the vacuum jacket. Moreover it is seen that thecollector iscoldestinthebellowss area, because of a larger area in this collector zone. The temperature gradient along the tube under atmospheric pressure conditions is lower,becausetheconvection in the glass enclosure provides amore uniformheatingover the entire lengthof the tube. In the case of the glass tube, the observed temperaturegradient is related to the gradientof the metal tube and the cooling at the ends of the collector, which also explains thegradientinthecaseofnon-vacuum conditions.An important result is that the metal - epoxy - glass regions remainat a maximum of 55 °C when the stainless steel tube is at 200 °C, indicating that the resin is stable under these conditions.

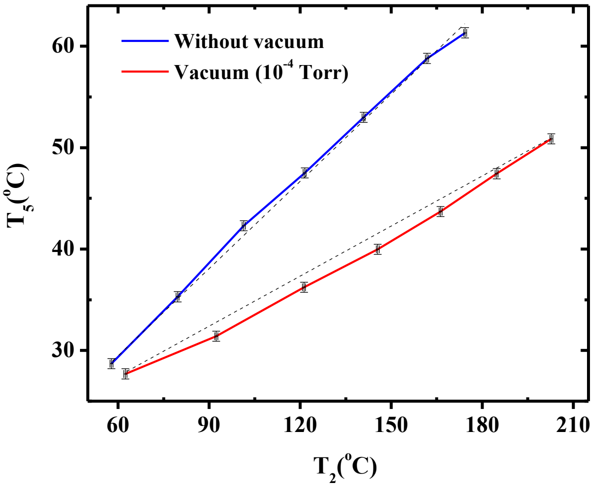

Fig.8. Glass heating when steel tube temperature is rising: T_5 and T_2 are the temperatures of the outside of the glass and at the middle of the stainless steel tube, respectively.

In order to compare the power loss of our collector with others reported in the literature we used equation 4.In Reference [1] this formula is the best choice to fit the experimental P_L(W/m) of their tubular evacuated collectors. In Figure (9) we show the best fit achieved with this equation for the total specific power loss P_L. Parameters ξ and βused in this fit were 0.21 ±0.01 and 1.7 ± 0.2 (x10^{-8}),respectively, which are slightly higher than those reported in the literaturewhere the corresponding values were 0.14 and 1.16 x10^{-8}, respectively[1].In our opinion,this effect is related to a highvalue of the thermal emittance of our selective coating and higher convection losses at the ends of collector.

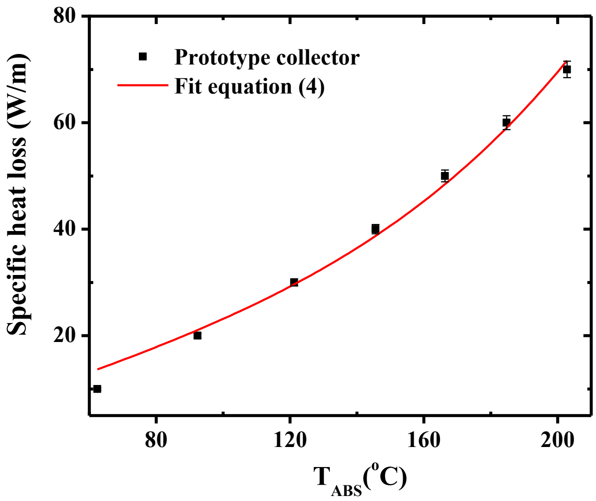

Fig.9. Experimental data fitting to Eq. (4) for specific heat loss.

5.3 The collector exposed to sunlight without concentration.

In order to determine the absorption characteristics of the selective coating deposited on the stainless steel tube, the collector was placed in the sun at an angle of 20 degrees with the horizontal, oriented towards the south and without any concentrator mirror. During this experiment, the pressure inside of the collector between the stainless steel and glass tubes was 70 Torr. The stainless steel tube was filled with water, and the water temperature was measured as a function of time of exposure to sunlight between 12:00 noon and 2:30 pm, during which solar radiation averaged 900 W/m^2 as measured with the radiometer at CINVESTAV-Mérida (20^o 58′ 12″ N and 89^o 37′ 12″ W). Figure (9) shows the temperature increases to reach a steady state temperature of about 72 ^{o}C.Considering onlythe direct incident solar radiation on the tube aperture area of 0.019 X 0.97 = 0.0184 m^2, we can estimate the maximum power of radiant energy that could reach the selective coating to be 0.0184 m^2 x 900 W/ m^2 ≈ 16 W. From figure (7), we can see that the power loss at 72 ^{o}C without vacuum is about 16 W. This good agreement between incident sun light power and power losses is an indication that the absorbance of our selective coating is high, as is demonstrated by the reflectance spectrum shown in figure (3).

Thissimple experimentby placingthe collectorin the sunwithout anyconcentrator mirrorshows, unsurprisingly, thatin these conditions itdoes not reach a temperatureof150^{o}Cneeded forthe application in the fried snack industry. If the experiment of exposure to sun had taken place with the glass tube at a vacuum of 10^{-4}Torr, the stagnation temperature would be expected to increase to about 80 ^{o}C. At 150 ^{o}C under vacuum conditions, the power loss is about 43 W. In order to obtain a 50% efficiency (η) at this temperature, the minimum required solar power on the collector tube would be estimated to be 104 W. This corresponds to 6.5 times the incident solar power without concentration; hence, with a concentration factor of 6.5, the collector could work with an efficiency of 50% at 150 ^{o}C.

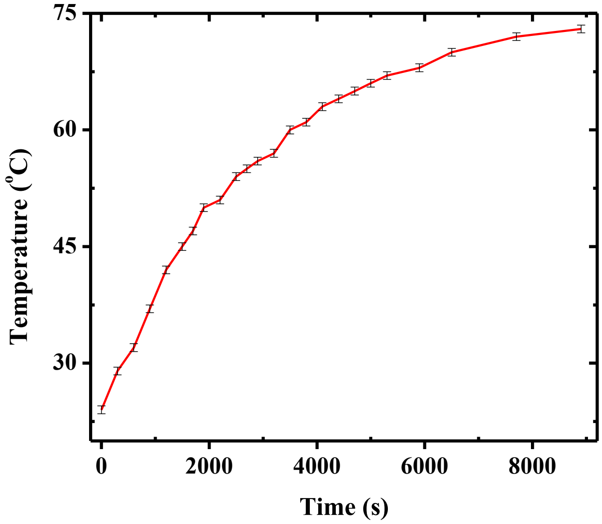

Fig.9. Temperature of water inside the stainless steel tube of the Ni/NiO-based collector as a function of exposure time to sunlight (about 900 W/m^2).

With 50 W heating power at 150 ^{o}C, we could expect an oil flow ($Power/C_p\,\Delta T$) of 0.8 liters per hour. In five hours of sunshine, we would have 4 liters heated up to 150 ^{o}C. In one year 1460 liters would be heated. To obtain this amount of oil heatedto 150 degrees, it takes 350 MJ (the efficiency of boiler is not considered). Taking in account that one kg of diesel is equivalent to ≈ 40 MJ, the production of the collector is equivalent to 350/40 = 8.7 liters which it is not very high. Nevertheless, increasing the concentration factor by using, for example, a parabolic trough mirror, this quantity can be increased to attractive values: with a concentration factor of 50 times, the quantity of energyproducedincreases to 11,230 MJ.

Conclusions

We have developed and characterized a prototype of an evacuated tubular solar collector with the aim to start a feasibility study of this type of technology to be developed for domestic and industrial applications. The systematic study of heat losses of the collector and sunlight exposure, indicate that:

1. At a pressure of 10^{-4}Torrin the space between the steel tube and the borosilicate glass, the suppressionof the convection - conduction mechanism isclearly shown.

2. The relatively high specific power losses (W/m) of our collectoris the result of a combination of a relatively high emissivity of the used selective coating and a strong contribution of convective losses in the non-isolated metal ends.The emissivity of the selective coating must be optimized through a more accurate control of theNiO layer thickness.

3. The collector can develop an efficiency of 50% at 150 °C, with a concentration factor of 6.5. Under these conditions, the corresponding oil flux would be poor. However with a concentration factor of 50, the performancecould be attractive.

4. The resultsof this studyrepresent an encouraging first stepin the development of a local solar technology, and provide a guide for future improvements of prototype collectors.

Acknowledgements

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