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DESIGN OF A FLAT PLATE SOLAR COLLECTOR FOR ABSORPTION-COOLING APPLICATIONS IN THE CARIBBEAN

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ABSTRACT

The present work deals with the design methodology of a high efficiency flat plate solar collector to be used in absorption cooling system and for climates like Puerto Rico and the Caribbean. Specialized software was used to simulate the thermal behavior of the solar collector and the mechanical stresses. Results such as the optimum thickness of insulation and spacing between the glass and the absorbing surface are given.

INTRODUCTION

In solar-fired absorption cooling systems is of great importance the performance of the solar collectors. The solar collectors not only represent the highest single investment of the components of the system but also the total energy supplied to the system, represented by the solar fraction, becoming also one of the parameters which determines the feasibility of the entire system. For this reason, when a solar system for cooling applications is designed, a high efficiency solar collector must be considered. Furthermore, by using high efficiency solar collectors the useful energy collected increases, increasing the storage tank temperature reducing the need for auxiliary energy [1]. Another important aspect that influences the solar collectors is the life cycle of the system which will increase with the durability of the solar components. With these considerations, the present work is focused in the design of a high performance solar collector for solar cooling applications. A flat plate was considered because it has advantages with respect to other types of solar collectors for low latitude locations such as Puerto Rico and the Caribbean [2]. A Fortran program was used for the optimization of the dimensions and materials of the collector and the finite element software package ANSYS was used to optimize the thickness of the frame and to calculate the mechanical and thermal stresses.

NOMENCLATURE

Symbols:

A: area (m^2)
 F_1 : circumsolar coefficient
 F_2 : brightness coefficient
I: hourly irradiation ($J/hr\ m^2$)
Q: heat transfer rate (W)
R: geometric factor
S: absorbed solar radiation (W/m^2)
T: temperature (K)
U: overall heat transfer coefficient ($W/m^2\ K$)

Greek Symbols:

α : absorptance
 β : collector tilt
 ρ : reflectance
 η : collector efficiency
 τ : transmittance

Subscripts:

a: ambient
b: beam
B: bottom
C: collector
d: diffuse
E: edge
g: ground
L: load
m: mean
p: plate
U: useful
T: top, tilted

THERMAL SIMULATION

A thermal simulation was performed for a flat plate solar collector under weather conditions for the location of Ponce, Puerto Rico. The program used is a modification of the program used by Hernández et al. [3] to simulate a solar collector under the solar radiation corresponding to the location of Ponce, Puerto Rico, where typical weather conditions are about 303 K and 64 % RH between 8:00 am and 5 pm. In the simulation, the solar radiation at the inclined collector's surface is estimated on a hourly and monthly basis for the chosen location of Ponce, using the Perez et al. model [4] and the absorbed solar radiation is calculated following the mathematical model in Duffie and Beckman [5]. The input fluid temperature considered for the simulation was 353.15 K, simulating the approximated temperature of the water leaving the generator of an absorption machine. The absorbed solar radiation per unit collector area can be expressed as:

$$S = I_b R_b (\tau\alpha)_b + I_d (1 - F_1) \left(\frac{1 + \cos \beta}{2} \right) (\tau\alpha)_d + I_d F_1 \frac{a}{b} (\tau\alpha)_b + I_d F_2 \sin \beta (\tau\alpha)_d + I \rho_g \left(\frac{1 - \cos \beta}{2} \right) (\tau\alpha)_g$$

Eq. (1)

The useful energy gain in the solar collector is expressed as:

$$Q_U = A_C [S - U_L (T_{p,m} - T_a)]$$

Eq. (2)

where U_L is the overall heat transfer coefficient and is expressed as:

$$U_L = U_T + U_B + U_E$$

Eq. (3)

The efficiency of the flat plate collector can be calculated using the expression:

$$\eta = \frac{Q_U}{A_C I_T}$$

Eq. (4)

MECHANICAL AND THERMAL STRESSES

The finite element package ANSYS was used to estimate the mechanical and thermal stresses of the frame of the solar collector. For the stress analysis it was considered a flat plate collector tilted 20 degrees from the horizontal and under wind velocity of 49.17 m/s (110 miles/hour) flowing against the collector. The dimensions used for the flat plate were 1.83 m (6 ft) length, 1.22 m (4 ft) wide, and 0.089 m (3.5 inches) thick. An "I" shape for the aluminum frame was considered and an aluminum plate was considered at the bottom and joined to the frame with rivets. A "Z"-shape maintains the glass in position over the frame with a band of EPDM rubber to seal the solar collector. Figure 1 shows the geometry used in the analysis.

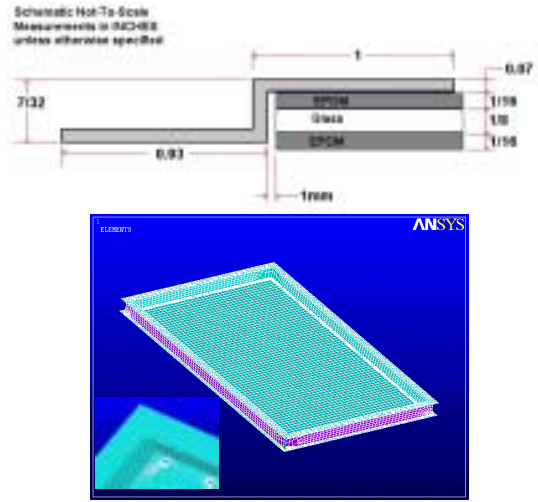


Figure 1: Geometry used for the Collector.

RESULTS

From the thermal performance analysis results for the insulation thickness at the bottom and edge of the collector were obtained, as well as the spacing between the glass and the absorbing surface and are presented in Fig. 2, 3 and 4. For all the cases the inlet water temperature for the collectors was considered 353.15 K to emulate the conditions prevailing at the outlet of a generator of an absorption machine. The insulation considered is urethane (polyisocyanurate) with a thermal conductivity of 0.026 W/m K @ 300 K [6]. The absorbent material used was a commercially available selective material having optical properties corresponding to a total solar absorptivity of 0.95 and infrared emission of 0.05, commercially referred as TINOX™.

In Fig. 2 it is shown the relationship between the collector efficiency and the bottom insulation thickness. From 0.0064 to 0.0127 m of bottom insulation thickness the relationship is practically linear with a high slope, from 0.0127 to 0.019 m the slope decreases, from 0.019 to 0.0254 m the slope increases again and for values higher than 0.0254 m a curve with a decreasing slope can be seen that approaches the line of 62% at the infinite. Depending on the application, values of 0.0254 m or more can be acceptable.

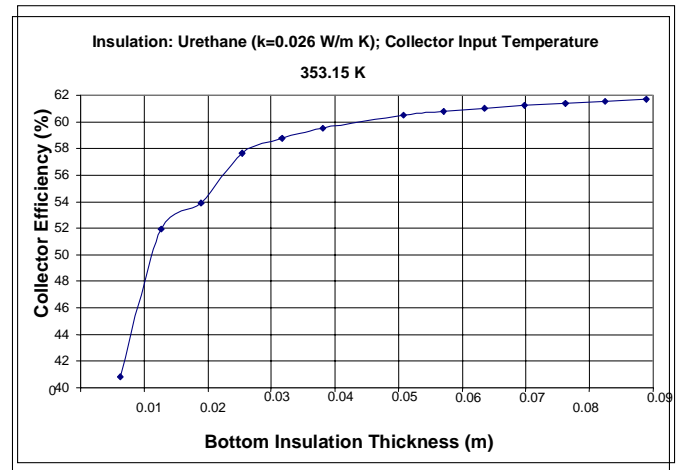


Figure 2: Bottom Insulation Thickness.

In Fig. 3 it is shown the relationship between the collector efficiency and the edge insulation thickness. As can be seen, for a thickness of 0.0254 m the collector efficiency is about 60.3%, and for thickness larger than 0.0254 m the increment in the collector efficiency decreases. In order to increase the collector efficiency by 1% from this point and on, it will be necessary to increase the edge insulation thickness in 0.0254 m.

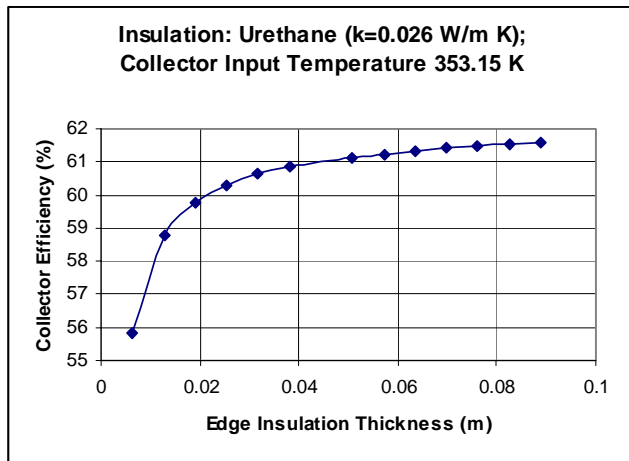


Figure 3: Edge Insulation Thickness.

In Fig. 4 it is shown the relationship between the collector efficiency and the cover to plate spacing. As can be seen here a value between 0.0254 m and 0.0508 m provides good values for the collector efficiency between 60.3% and 62.7%. More than 0.0508 m of the cover to plate spacing produces low increases in the collector efficiency.

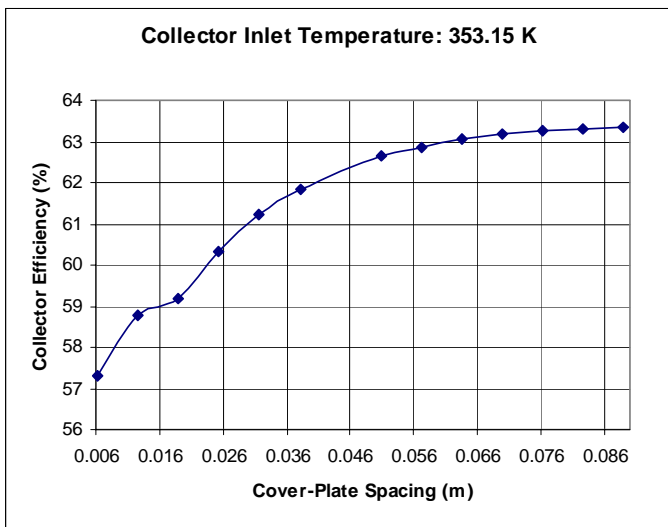


Figure 4: Cover to Plate Spacing.

Results for the mechanical stress analysis are shown below. An analysis for the material of the frame was done for different thicknesses of the aluminum plate at the back of the collector, 0.000508, 0.0008128, and 0.001016 m (0.02, 0.032, and 0.040 inches). As mentioned before, aluminum was considered and different alloys were analyzed for resistance as shown in Fig. 5. For the wind velocities of 49.17 m/s (110

Miles/hour) the AA6063-T5 aluminum alloy presents better resistance than the others considered.

For the plate a commercial aluminum alloy was used in the stress analysis and the results are shown in Fig. 6. As can be seen the AA6262-T6 aluminum alloy is resistant enough for this application.

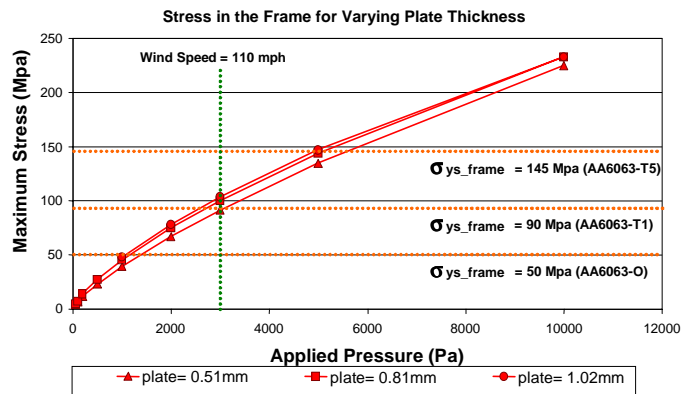


Figure 5: Frame Materials.

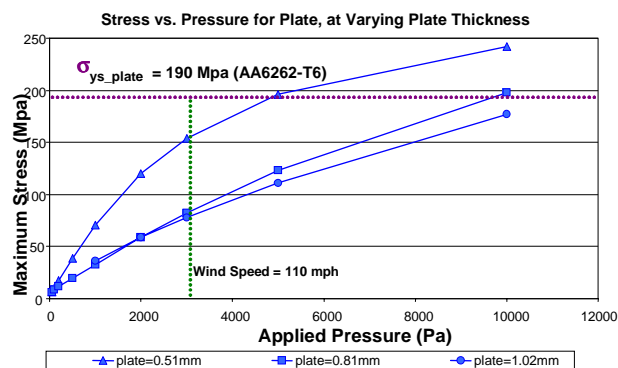


Figure 6: Plate Material.

The stress and deflection for a frame thickness of 0.001778 m (0.07 inches) is shown in Table 1. This thickness was considered because it is the minimum thickness permitted for extrusion. As seen, the maximum stress was found to be 115 MPa and the maximum deflection was 0.001372 m.

Maximum Stress (x-direction)	Maximum Deflection (x-direction)
115 MPa	0.001372 m

Table 1: Maximum Stress and Deflection in the Frame.

The deflection of the aluminum plate under the conditions of wind velocity of 49.17 m/s (110 Miles/hour), for plate thickness: 0.000508, 0.0008128, and 0.001016 m (0.020, 0.032, and 0.040 inches) is 0.018, 0.015, and 0.014 m respectively, as shown in Fig. 7. The deflection of the frame is shown again for different plate thickness and results are similar as those found in Fig. 5.

It must be mentioned that the possibility of adding elements to reinforce the plate was explored and it was found to be inconvenient and uneconomical.

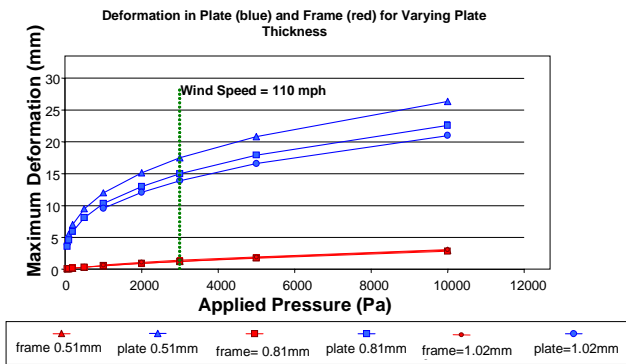


Figure 7: Deformation in the Plate and Frame.

Results for the strip used to place the glass in position and to seal the collector are shown in Table 2. The aluminum alloy and thickness for the strip are the same as for the frame: AA6063-T5 and 0.001778 m (0.07 inches), respectively. The modulus of elasticity for the aluminum, the EPDM rubber, and the glass used for the simulation are 69×10^9 , 0.138×10^6 , and 10×10^{10} Pa respectively. The maximum pressure applied on the EPDM rubber must be 62052 Pa (9 psi) [7] and this is the value used in the design simulation.

As shown in Table 2, the maximum stress in the strip is below the maximum stress of the aluminum alloy of 145 MPa, and the maximum deflection of the strip is 0.00339 m.

Maximum Stress (x-direction)	Maximum Deflection (x-direction)
77.1 MPa	0.00339 m

Table 2: Maximum Stress and Deflection in the Strip.

An analysis of the thermal expansion of the tubes inside the solar collector was also conducted. A tube diameter of 0.01905 m ($\frac{3}{4}$ inches) was considered for the header and 0.0127 m ($\frac{1}{2}$ inches) for the fin's tubes. These are typical values used in flat plate collectors in Puerto Rico. The material for the tubes is copper. The maximum expansion of 0.0021 m was found along the axis of the headers and of 0.0028 m along the axis of the fin's tubes.

The maximum thermal expansion of the glass was found to be 0.001 m along the major dimension. A glass of 1.854 m (73 inches) x 1.143 m (45 inches) was considered. The number of fins per collector was 9 and the reference temperature for the thermal expansion calculation was 368.15 K.

ASSEMBLY OF THE SOLAR COLLECTOR

The solar collector was finally assembled at the facilities of Caribbean Thermal Technologies Inc., in Mayaguez, Puerto Rico, as shown in Fig. 8. Aluminum was used for the frame and the back, TINOX™ selective absorber surface was used for the fins, low-iron tempered glass for the cover, and urethane as the insulation.



Figure 8: High Efficiency Solar Collector

The production cost for this collector is estimated in \$300. Actually, the collector is under testing at the laboratory of Caribbean Thermal Technologies Inc.

CONCLUSIONS

In this paper, a methodology for the design of a high performance flat plate collector was presented. The design approach takes into consideration thermal performance as well as mechanical performance. The conclusions are:

A bottom insulation thickness of 0.04445 m to 0.0508 m (1.75 to 2 inches) is recommended for a flat plate collector and for a climate like Puerto Rico.

A minimum edge insulation thickness of 0.0254 m (1 inch) is recommended. Larger values will not make significant difference in the collector's efficiency.

For the spacing between the glass and the absorbing surface, a value between 0.0254 to 0.0508 m (1 to 2 inches) is recommended to be used.

The minimum thickness of 0.001778 m (0.07 inches) required for extrusion of the aluminum shape used in the frame and in the strip of the collector, provides sufficient resistant under the conditions of hurricane winds of 49.17 m/s (110 Miles/hour; equivalent to a pressure of 3000 Pa), and rigid enough to seal the glass against the frame, so it is recommended to be used in solar collector's frames.

Aluminum alloy AA6063-T5 is recommended for the construction of the collector frame, and AA6262-T6 commercial alloy for the plate.

The effect of the thermal expansion of the cooper tubes and the glass is minimum having a small impact in the design of the solar collector.

ACKNOWLEDGMENTS

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