Evaluation of incident radiation by a V-Concentration System (VCS) in Bogotá, D.C.*

Evaluación de la radiación incidente por un sistema de concentración en V (SCV) en Bogotá, D.C.*

Avaliação da radiação incidente por um sistema de concentração V (VCS) em Bogotá, D.C. *

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Abstract

The study presents the behavior of a V concentration system (VCS), as a way to estimate the incident radiation on a flat surface, based on the solar coordinates described in the equations of Spencer, J.W.

Increasing the areas of solar capture is a way to expand the solar radiation, captured on a flat surface by reflection. Maximizing the fraction of solar radiation captured; for that purpose, the V-Concentration System (VCS) was developed, adding four flat mirror surfaces to a flat surface, each with an inclination angle to the (flat) pickup surface. A statistical model was described to find a regression and thus expose the specific behavior areas of reflection on the (VCS), with the purpose of finding the optimal angle which achieves an increase in the uptake of radiation on a flat surface.

Keywords: V-Concentration System (VCS), Incident Radiation, Flat Surface, Solar Radiation, Reflection.

Resumen

Se presenta un estudio para observar el comportamiento de un sistema de concentración en V (SCV), como medio para estimar la radiación incidente sobre una superficie plana, con base en las coordenadas solares descritas en las ecuaciones de Spencer, J. W.

Aumentar las áreas de captación solar es una forma para incrementar la radiación solar capturada por una superficie plana por medio de la reflexión. Maximizando la fracción de radicación solar captada; para tal propósito fue desarrollado el sistema de concentración en V (SCV), que agrega cuatro superficies de espejos planos a una superficie plana, cada una con un ángulo de inclinación respecto a la superficie de captación (plana). De estos se elaboró un modelo estadístico para encontrar una regresión y así exponer el comportamiento específico de las áreas de reflexión del (SCV), con el propósito de encontrar el ángulo óptimo que lograra un incremento en la captación de radiación sobre la superficie plana.

Palabras clave: Sistema de concentración en V (SCV), Radiación incidente, Superficie plana, Radiación solar, Reflexión.

Resumo

Um estudo é apresentado para observar o comportamento de um sistema de concentração V (VCI), como um meio de estimar a radiação incidente em uma superfície plana, com base nas coordenadas solares descritas nas equações de Spencer, J. W.
Aumentar as áreas de captação solar é uma forma de aumentar a radiação solar captada por uma superfície plana por meio da reflexão. Maximizar a fração de radiação solar capturada; Para este propósito, foi desenvolvido o sistema de concentração em V (SCV), que adiciona quatro superfícies de espelhos planos a uma superfície plana, cada uma com um ângulo de inclinação em relação à superfície de coleta (plana). A partir deles, um modelo estatístico foi desenvolvido para encontrar uma regressão e, assim, expor o comportamento específico das áreas de reflexão (SCV), a fim de encontrar o ângulo ideal que alcançaria um aumento na captação de radiação na superfície plana.

Palavras-chave: V-Concentration System (SCV), Radiação incidente, Superfície plana, Radiação solar, Reflexão.

Introduction

The main propose of the present investigation is to show the behavior of a concentration system in V. At estimating the capture of incident radiation on a flat surface, thorough the reflection emitted by the inclined reflective surfaces (mirrors). The methodology used for the development of the research is shown in Figure 1.

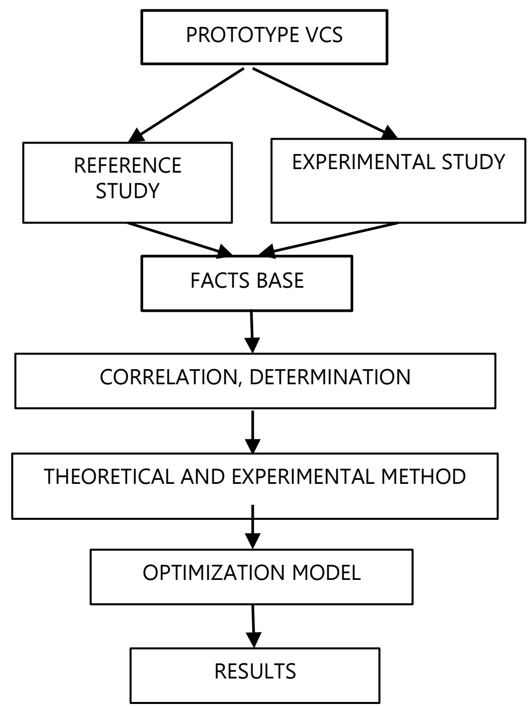


Figure 1. Research methodology. Source: Authors.

First, the prototype of the V-concentration system was developed, which consists in adding four surfaces of flat mirrors to a flat collection surface, at different angles of inclination and a certain height, in order to collect experimental primary data.

Secondly, the mathematical calculation of reference was developed, with the objective of obtaining the average daily and annual global solar radiation of the system, based on mathematical methods provided by Spencer, JW and the information of governmental entities such as the Institute of Hydrology, Meteorology and Studies. Environmental IDEAM, and the Mining and Energy Planning Unit (UPME).

Subsequently, a statistical model was made, which achieved the best combination of the parameters that make up the V-concentration system, based on the results obtained from the theoretical and experimental calculation, the areas and angles of inclination of the reflective surfaces.

Finally, the behavior of the reference model was evaluated and the experimental one with the radiation obtained with the VCS.

Methodology

VCS Prototype

The prototype of the VCS consists in a flat surface and the four reflecting surfaces as illustrated in Figure 2, and in Figure 3, the prototype dimensions are shown. The aim of the prototype is to expand the areas of solar incidence on the reflecting surfaces; so by this mean the reflection on the flat surface would increase the solar uptake.

Figure 2. VCS prototype
Source: Authors.

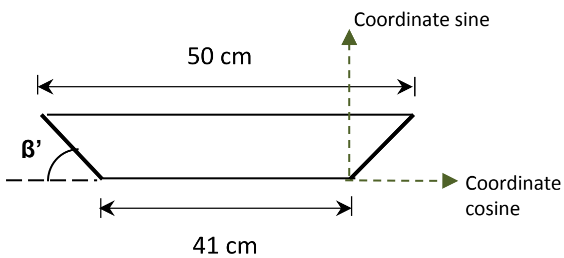


Figure 3a. VCS prototype dimensions
Source: Authors.

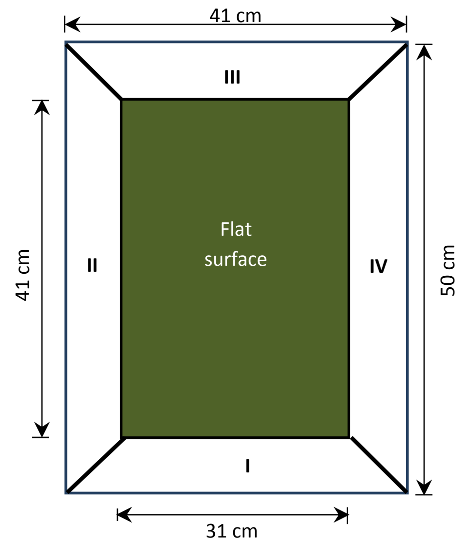


Figure 3b. VCS prototype dimensions
Source: Authors

Where:

Base surface
Reflected area

I = Surface I
II = Surface II
III = Surface III
IV = Surface IV
β '= Angle by surface
Height reflective surfaces = 10 cm

Reference study

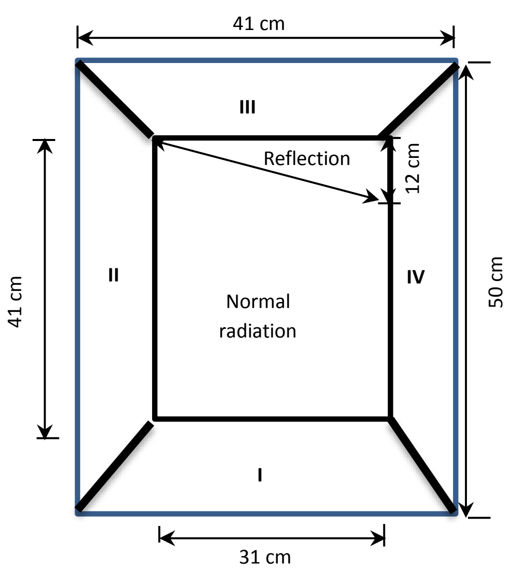
The objective of the reference study was to calculate the total daily H (B) radiation captured by VCS, based on the equations described by Spencer, in the solar Atlas, this information serves as a basis to correlate with the experimental data, and thus to be able to pose the model.

The objective of the reference study was to calculate the total daily H (B) radiation captured by VCS, based on the equations described by Spencer, in the solar Atlas, this information serves as a basis to correlate with the experimental data, and thus to be able to pose the model.

Experimental study

In days with direct irradiation in Bogotá, experimental data were taken. The prototype was placed to the south with a constant 5 ° inclination angle of the base surface in order to take samples and photographs, the reflecting surfaces with variable angles: 15 °, 30 °, 45 ° and 60 °, hour by hour in order to observe the behavior of the reflection, an example, is shown in Figure 4. It showed that the VCS forms different areas; areas of shadows, which indicate that the incidence of solar rays on reflecting surfaces is zero, areas of normal reflection, indicates that the incidence of solar rays is perpendicular to the flat surface, data that is not taken into account in the investigation and reflection areas that indicate the sun's rays affect the reflective surfaces and reflect on the flat surface; this was important data for the relevant database in the development of the model.

With the above information, the incident areas were graphed and marked on the flat surface, in order to obtain a total experimental H (β) radiation, the procedure was as follows: the fractions of shadow areas are calculated, and the areas of reflection, hour by hour, then the sum of the fractions of calculated areas is elaborated, with the reference H (β) obtained. Table 1 lists the results.



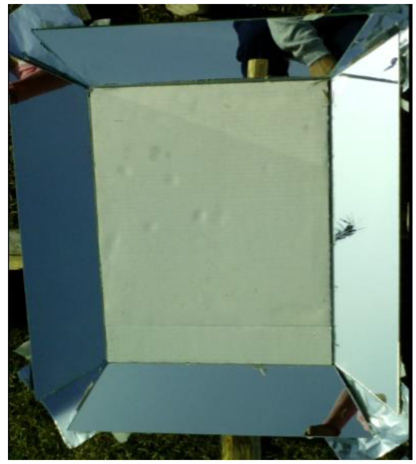


Figure 4. Reflection area at 8 am with angle 30 °
Source: Authors.

Table 1.
Global solar radiation of the system.

Inclination angle (β)	Experimental radiation H(β) (kWh/m²)	Theoretical radiation H(β) (kWh/m²)
0	3,880	3,82
15	3,882	3,81
30	4,180	3,76
45	3,879	3,68
60	4,336	3,57
15	3,858	3,81
30	4,364	3,76
45	4,001	3,68
60	4,434	3,57

Source: Authors.

Table 2.
Areas and angles of each surface, and Calculation of sines and cosines of each of the angles.

(β)	Areas (cm²)					Angles (°)					Cosines (rad)					Sines (rad)				
	Base	S1	S2	S3	S4	Base	S1	S2	S3	S4	Base	S1	S2	S3	S4	Base	S1	S2	S3	S4
0	1271	360	460	360	460	5	5	90	-5	-90	0,996	1,00	0,00	1,00	0,00	0,09	0,09	1,00	-0,09	-1,00
15	1271	360	460	360	460	5	20	75	-10	-75	0,996	0,94	0,26	0,98	0,26	0,09	0,34	0,97	-0,17	-0,97
30	1271	360	460	360	460	5	35	60	-25	-60	0,996	0,82	0,50	0,91	0,50	0,09	0,57	0,87	-0,42	-0,87
45	1271	360	460	360	460	5	50	45	-35	-45	0,996	0,64	0,71	0,82	0,71	0,09	0,77	0,71	-0,57	-0,71
60	1271	360	460	360	460	5	65	30	-55	-30	0,996	0,42	0,87	0,57	0,87	0,09	0,91	0,50	-0,82	-0,50
15	1271	360	460	360	460	5	20	75	-10	-85	0,996	0,94	0,26	0,98	0,09	0,09	0,34	0,97	-0,17	-1,00
30	1271	360	460	360	460	5	35	60	-25	-60	0,996	0,82	0,50	0,91	0,50	0,09	0,57	0,87	-0,42	-0,87
45	1271	360	460	360	460	5	50	45	-35	-45	0,996	0,64	0,71	0,82	0,71	0,09	0,77	0,71	-0,57	-0,71
60	1271	360	460	360	460	5	65	30	-55	-30	0,996	0,42	0,87	0,57	0,87	0,09	0,91	0,50	-0,82	-0,50

Source: Authors.

Table 3.
Areas of reflection of the surfaces

(β)	Reflected area at the cosine (cm²)					Reflected area at the sine (cm²)					Captured energy (kWh/m²)	
	Base	SI	SII	SIII	SIV	Base	SI	SII	SIII	SIV	Theory	Experimental
0	1.266	359	0	359	0	111	31	460	-31	-460	3,82	3,880
15	1.266	338	119	355	119	111	123	444	-63	-444	3,81	3,882
30	1.266	295	230	326	230	111	206	398	-152	-398	3,76	4,180
45	1.266	231	325	295	325	111	276	325	-206	-325	3,68	3,879
60	1.266	152	398	206	398	111	326	230	-295	-230	3,57	4,336
15	1.266	338	119	355	40	111	123	444	-63	-458	3,81	3,858
30	1.266	295	230	326	230	111	206	398	-152	-398	3,76	4,364
45	1.266	231	325	295	325	111	276	325	-206	-325	3,68	4,001
60	1.266	152	398	206	398	111	326	230	-295	-230	3,57	4,434

Source: Authors.

In Table 1, it is exposed that the system presents a greater solar uptake when the angle of inclination of the four reflecting surfaces is 60 °, obtaining an H (β) of 4.336 kWh / m2 and 4.434 kWh / m2 which indicates an increase in global radiation compared to the reference value which corresponds to 3.57 kWh / m2 at 60 °.
The areas of each surface with their respective angles of inclination with respect to the flat surface are shown (Table 2). The sine and cosine of the angles of each surface are calculated, data needed to realize the product of the areas with the sines and cosines in order to find the reflection areas of the surfaces with respect to the coordinates in cosine and sine, match in Table 3.
The database results from Table 3. From these, reflective areas, (cm^2), in cosine and sine and the theoretical and experimental energy captured (kWh/m^2), the correspondence between the variables and their relevance to the effect of the reflected area to propose a model.

Correlation coefficients.

The **Pearson correlation coefficient** (named after Karl Pearson, who formulated it) is a measure used in Statistics to calculate the degree of linear relationship between two random variables, therefore, it is also known as the **linear correlation coefficient**.

The correlation coefficients are determined by Excel. Among the following pairs of variables: the theoretical measure vs. the experimental, the theoretical measure vs each of the areas reflected in cosine and sine, as well as the experimental measure vs each of the areas reflected in cosine and sinus, with the purpose to quantify the proportion of resemblance (correlation) and explanatory (determination) between the pair of variables, as shown in the matrix of Table 4 and 5.

The data design leads to a multicollinearity situation which means that there is a strong correlation between each pair of variables mentioned above. For example, in Table 4, it is observed that the correlation coefficient between the theoretical and experimental measure is -0.66, which means that the experimental values go in a direction opposite to the theoretical ones. When finding the coefficient of determination, for the same pair of variables, in Table 5, it is 44% that is to say that the behavior of the theoretical explains 44% of the experimental information, therefore, each one has an independent behavior 56%.

When comparing the correlations between the experimental measure vs the projected areas, from Table 4, it is identified that all have a value greater than 0.66, that is to say that all the surfaces have some contribution or decrease in the average value of the captured radiation measured experimentally, the above can be evidenced, so that all have a coefficient of determination higher than 44%, according to Table 5.

Table 4.
Correlation results

Correlations	*Measure*	*Theoretical*	*Cosine SI*	*Cosine SII*	*Cosine SIII*	*Cosine SIV*	*Sine SI*	*Sine SII*	*Sine SIII*
Theoretical	-0,66								
Cosine SI	-0,67	1,00							
Cosine SII	0,67	-0,93	-0,95						
Cosine SIII	-0,72	0,99	0,98	-0,89					
Cosine SIV	0,68	-0,93	-0,95	0,99	-0,88				
Sine SI	0,67	-0,92	-0,95	1,00	-0,88	0,99			
Sine SII	-0,66	1,00	1,00	-0,94	0,99	-0,93	-0,93		
Sine SIII	-0,73	0,98	0,99	-0,98	0,96	-0,98	-0,97	0,98	
Sine SIV	0,67	-1,00	-1,00	0,94	-0,98	0,94	0,93	-1,00	-0,98

Source: Authors.

Table 5.

Determination results.

Determinations	*Measure*	*Theoretical ca*	*Cosine SI*	*Cosine SII*	*Cosine SIII*	*Cosine SIV*	*Sine SI*	*Sine SII*	*Sine SIII*
Theoretical	0,44								
Cosine SI	0,45	1,00							
Cosine SII	0,45	0,87	0,91						
Cosine SIII	0,51	0,98	0,96	0,79					
Cosine SIV	0,47	0,86	0,90	0,97	0,78				
Sine SI	0,45	0,85	0,90	1,00	0,78	0,97			
Sine SII	0,44	1,00	1,00	0,89	0,97	0,87	0,87		
Sine SIII	0,53	0,95	0,97	0,96	0,91	0,95	0,95	0,96	
Sin SIV	0,45	1,00	1,00	0,88	0,97	0,89	0,87	1,00	0,97

Source: Authors.

The correlation between the theoretical measure vs each one of the areas reflected in cosine and sine, of Table 4, is higher than 92% and this is reflected in the coefficients of determination above 85%, shown in Table 6, therefore, a high degree of correspondence is identified between the reflective areas of the theoretical and experimental studies. For this reason, a simple linear regression model is proposed.

Simple linear regression model.

$$Y = B_o + B_i X_i \quad (1)$$

- Y = Daily average, (kWh/m^2), of solar radiation based on the variable X_i
- B_o= coefficient, (kWh/m^2), for the intercept of the data, based on the surface of the base.
- B_i= estimated coefficient, (kWh/m^4), of the contribution per square meter, based on the projected surface.
- X_i= fixed term or intercept, corresponding to the surface of the base or projected, m^2.

Formulation of the model.

For the construction of the specific model for the case studied, it was necessary to obtain the coefficients (B), that is a **multiplicative factor**, or constant number that is on the left of a variable or unknown, and multiplies it, in order to determine the energy captured by the VCS; by means of a statistical regression analysis in Excel, with a confidence interval of 95%, of the theoretical and experimental measure vs. the areas reflected in cosine and sine.

The summary of the models associated with the experimental data and the theoretical data found are shown in Tables 6 and 7. The first column contains the area or variable of which we are speaking, it is to remember that each area has a sine projection and another of cosine; the next column (r) is the correlation coefficient, indicates the similarity by projection; then the coefficient of determination follows (r^2); later there is the statistic (F) calculated in the regression; followed by stevedores of the model in the intercept and that of the variable.
The last two columns are associated with the probability of rejecting the coefficient of the intercept, the coefficient of the variable and the model. In this case, since there is only one independent variable, the P value of the model and the variable are the same.

In Table 6, it is observed that the correlation coefficients for the experimental data are not higher than 0.74, therefore, the adjusted r squared coefficients are not greater than 0.47. However, in all cases the maximum permissible error level in the model is 0.051, that is, 5.1%.

For the theoretical data models, Table 7, there are correlation coefficients between 0.92 and 1.00. Which implies coefficients of determination between 0.83 and 1.00; all the F values are greater than 40 and the significance of the intercept, models and variable in all cases have an error level lower than 0.001, that means, they are lower than one error in each 1000.

Therefore, it can be identified that the models provide information, through the respective coefficients of the daily energy average captured in kilowatts per hour for each surface in each of the cosine and sine components, thus with the previous coefficients it is possible have the information required to propose the optimization model.

Table 6.
Summary of models associated with experimental data.

Area, experimental data	r	r^2 adjusted	F	Intercept	Coefficients	Intercept of P value	Model and variable of P value
Surface cosine I	0,67	0,37	5,67	4,643	-0,0021	0,000	0,049
Surface cosine II	0,67	0,37	5,76	3,798	0,0012	0,000	0,047
Surface cosine III	0,72	0,44	7,37	4,981	-0,0030	0,000	0,030
Surface cosine IV	0,68	0,39	6,18	3,823	0,0011	0,000	0,042
Surface sine I	0,67	0,37	5,70	3,743	0,0016	0,000	0,048
Surface sine II	0,66	0,36	5,52	4,748	-0,0018	0,000	0,051
Surface sine III	0,73	0,47	8,03	3,784	-0,0018	0,000	0,025
Surface sine IV	0,67	0,37	5,67	4,743	0,0018	0,000	0,049

Source: Authors.

Table 7.

Summary of models associated with the theoretical data.

Area and theoretical data	r	r^2 adjusted	*F*	Intercept	Coefficients	intercept of P value	Model and variable of P value
Surface cosine I	1,00	0,99	1.410,19	3,384	0,0013	0,000	0,000
Surface cosine II	0,93	0,85	45,14	3,876	-0,0007	0,000	0,000
Surface cosine III	0,99	0,98	314,72	3,222	0,0016	0,000	0,000
Surface cosine IV	0,93	0,84	42,08	3,859	-0,0006	0,000	0,000
Surface sine I	0,92	0,83	40,18	3,906	-0,0009	0,000	0,000
Surface sine II	1,00	1,00	7.669,80	3,318	0,0011	0,000	0,000
Surface sine III	0,98	0,95	147,26	3,878	0,0010	0,000	0,000
Surface sine IV	1,00	1,00	2.446,81	3,324	-0,0010	0,000	0,000

Source: Authors.

Construction of the model

With the calculated coefficients we already have the information required to propose a linear statistical model for the case study, in order to evaluate the best combination of the parameters that make up the MCS, to find the increment of incident radiation on the surface flat

For its construction was used:
a) Structural design. Figure 5
b) Theoretical and experimental data base.
c) Objective function
d) Regression coefficients
e) Set of assumptions and restrictions.
The following model is formulated. Which is carried to a linear program of the VCS.

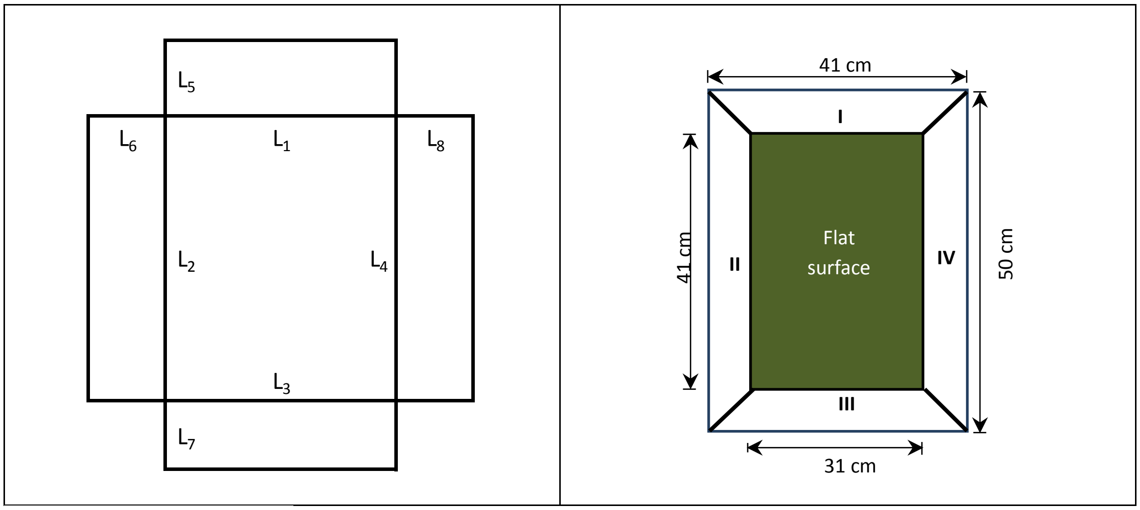


Figure 5. Variable system. Source: Authors.

Objective function

$$E = \beta_{Exo}L_1L_2C_0 + \beta_{Ex1}L_1L_5C_1 + \beta_{Ex2}L_2L_6C_2 + \beta_{Ex3}L_1L_7C_3 + \beta_{Ex4}L_2L_8C_4 + \beta_{Exo}L_1L_2S_0 + \beta_{Ex5}L_1L_5S_1 + \beta_{Ex6}L_2L_6S_2 + \beta_{Ex7}L_1L_7S_3 + \beta_{Ex8}L_2L_8S_4 \quad (2)$$

Results

Mathematical models proposed
Reference model:

$$\mathrm{E} = 0{,}00028\mathrm{L_1L_2C_0} + 0{,}00125\ \mathrm{L_1L_5C_1} - 0{,}00066\mathrm{L_2L_6C_2} + 0{,}00163\mathrm{L_1L_7C_3} - 0{,}00061\mathrm{L_2L_8C_4} + 0{,}03248\mathrm{L_1L_2S_0} - 0{,}00089\mathrm{L_1L_5S_1} + 0{,}00110\ \mathrm{L_2L_6S_2} + 0{,}00098\mathrm{L_1L_7S_3} - 0{,}00108\mathrm{L_2L_8S_4} \quad (3)$$

Table 8.
Theoretical captured radiation vs theoretical model

Inclination angle (β)	Theoretical radiation H(β) (kWh/m2)	Radiation with theoretical model H(β) (kWh/m2)
0	3,82	3,904
15	3,81	4,975
30	3,76	4,518
45	3,68	3,998
60	3,57	3,451

Source: Authors.

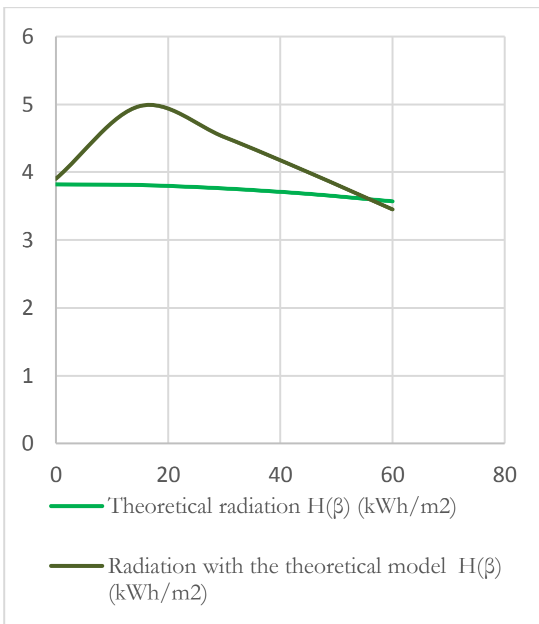


Figure 6. Theoretical captured radiation vs theorical model. Source: Authors.

In Table 8 and Figure 6, the behavior of the reference model vs the theoretical radiation is shown, a very similar uptake between the different angles of inclination of the reflective surfaces can be observed, which indicates it is not relevant, so that the VCS theoretically would not work.

Experimental model:

$$\begin{aligned} E = 0{,}00340L_1L_2C_0 - 0{,}00210L_1L_5C_1 \\ + 0{,}00120L_2L_6C_2 \\ - 0{,}00296L_1L_7C_3 \\ + 0{,}00113L_2L_8C_4 \\ + 0{,}00038L_1L_2S_0 \\ + 0{,}00162L_1L_5S_1 \\ - 0{,}00183L_2L_6S_2 \\ - 0{,}00184L_1L_7S_3 \\ + 0{,}00181L_2L_8S_4 \end{aligned} \quad (4)$$

Table 9.

Radiation captured experimental vs experimental model.

Inclination angle (β)	Experimental radiation H(β) (kWh/m2)	Experimental radiation with experimental model H(β) (kWh/m2)
0	3,88	3,778
15	3,87	1,952
30	4,27	2,764
45	3,94	3,679
60	4,39	4,634

Source: Authors.

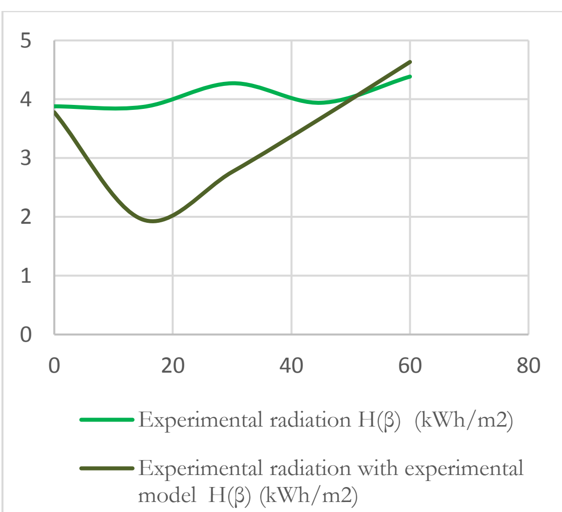


Figure 7. experimental captured radiation vs experimental model Source: Authors.

In Table 9 and Figure 7, the behavior of the experimental model vs experimental radiation is shown, an increase in the uptake can be observed when the VCS presents a 60 ° inclination, which indicates that it is possible to adapt a flat panel to an VCS to increase solar gain.

Conclusions

The experimentally measured data show that the flat surface without VCS has a solar radiation catchment of 3.88 kWh / m2, when coupling the VCS at an angle of 60 ° with respect to the flat surface, it increases to 4.39 kWh / m2, equivalent to an additional 11.5% of catchment.

When checking the experimental model, it is observed that the flat surface without VCS has a solar radiation catchment of 3.77 kWh / m2, when coupling the VCS at an angle of 60 ° with respect to the flat surface, it increases to 4.63 kWh / m2, equivalent to an additional 18.5% of catchment.

Based on the above, it is shown that it is possible to increase the solar uptake by means of the reflection provided by the V-concentration system and to improve the use of incident solar radiation on the flat surface in Bogotá.

The results show that the solar uptake depends on the inclination angle of the system, the reflection areas involved in the flat surface, the angle of solar incidence and the climatic conditions of the site.

The mathematical model developed based on the experimental and theoretical study indicates that the V-concentration system can be adjusted to the physical conditions of a flat solar panel.

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