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TRNSYS Modeling of flat plate and vacuum tube solar collector systems for residential use under equatorial middle altitude climate condition

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Abstract. In this work, residential solar systems were simulated to predict feeding domestic hot water, using TRNSYS (TraNsient SYstem Simulation software), under the operating conditions in Cuenca, Ecuador. The type of research is quantitative and with a correlational approach. Using data from an experimental test, a technical sheet was prepared that sought to identify the main variables to be applied in the model. The diffuse and direct radiation data were obtained by applying the isotropic diffuse model. When simulating in the software, the results show that the system presents an efficiency of 56.54% when heating water in a range of 30° to 45 °C. For the validation of the model, the chi-squared statistical test was applied, with which it was determined that the simulated data follow the same distribution as the real data.

Key words. TRNSYS, Flat plate collector, vacuum tube collector, system simulation.

1. Introduction

To reduce burning of fossil fuels and CO_2 emissions caused by anthropogenic activities, there are different sources of renewable energy or green energy, among which solar show the best potential for in-site self-supply [1]. The interest in taking advantage of solar energy has been around since centuries ago [2], [3], since it is: "An abundant, non-sequestering and non-polluting source of energy that can be collected to produce thermal energy for: heating water, cooking, dehydration, distilling liquids and producing electricity" [4].

Applying non-conventional renewables such as solar thermal (ST) energy implies a contribution to the sustainable development of cities and contribute to energy needs also, without reducing limited energy sources in the future [5] [6]. The analyzed technologies of solar thermal (ST) collectors are mainly considered for low-temperature requirements, then for heating domestic hot water (DHW) therefore it is one of the main applications of this technology [7]. These systems are subject to transitory functionality, which means change over time. The efficiency varies with climatic and use conditions. The use of transient simulation tools allows establishing realistic simulations of operating conditions in different scenarios without the need to locate or build expensive infrastructure [8].

It is estimated that through the application of this type of technology in the city of Cuenca (Ecuador) where this analysis takes place, a decrease of approximately 44% CO_2 caused by DHW preparation could be obtained, thus avoiding the emission of 108,535 tons of CO_2 into the environment per year [9]. In addition, it is expected a 14.25% reduction in fuel consumption, which represents 68.2% of the liquefied petroleum gas (LPG) requirements in the city. Under these perspectives, it is necessary to analyze the performance of ST systems at the local level, so as to enhance their use and demonstrate the advantages over conventional systems. In particular, the study area has almost constant climatic conditions throughout the year in concordance with local typical energy consumption. In this sense, the use of dynamic models allows establishing different scenarios, which can be simulated to observe the technological capacity, considering different ST technologies and under different configurations of orientation and inclination [10].

Fig. 1. Solar collectors installed at different orientations and inclinations.

This work characterizes the performance of solar collectors to obtain DHW in the city of Cuenca, using the TRNSYS software [11]. The results obtained will be contrasted with the real measurements obtained in four systems installed at the University of Cuenca (Figure 1). These systems are made up of two ST systems feed by two solar collectors technologies and operating in a way that simulates the demand conditions of a single-family residence. With this, the representative performance of a residential scenario is determined, as well as the performance under different orientations and inclinations of the solar collectors of both technologies. To calculate the incident radiation on a sloped surface in the study area, the Isotropic Diffuse model is applied.

2. Methodology

The location of the facilities to be analysed is on the University of Cuenca central campus, emplaced at 2°54'02" south latitude and 79°00'39" west longitude coordinates. The campus and the city is located at 2535 meters above sea level. Then to validate the simulation model, the real outlet temperatures of each collector are compared with the temperatures in the virtual analysis. With the real outlet temperatures, the difference could be calculated for each hour period. The analyzed ST systems corresponds to two complete systems feed by a flat plate solar collector each (signed as FPC01 and FPC02) and two ST systems feed by a evacuated tube solar collector each (ETC01 and ETC02). Each of the FPCs feeds a 200 L storage tanks and the ETC systems feed a 300 L storage tank each. Temperature data from these four solar thermal systems were obtained through sensors deployed at the outlet of each collector. Controls and data loggers have been installed in each thermal system to report operating conditions. These data correspond to temperature fluctuation on each collector outlet, and of the storage tanks also. Information regarding the radiation conditions and the temperature of the water that feeds the system has also been taken.

The climate file format required by TRNSYS needs the diffuse and direct components, therefore the Liu and Jordan model [12] was applied to calculate these components from global radiation data. The meteorological data and the incidence of radiation were registered on the meteorological station of the University of Cuenca, located less than one hundred meters from the location of the solar heating systems.

Using the TRNSYS interface, the thermal network and the connections for each thermal solar system were made. Figure 2 shows the general model of the connections developed in the software. The model in TRNSYS allows to obtain the total solar radiation on an sloped surface during an hourly period of time, through the sum of the three components: direct radiation, diffuse radiation and reflected radiation or albedo from the mathematical model (1) proposed by Duffie and beckman [13].

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I_{Pg}\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

Where,
I_T, is the total radiation
I_b, is direct radiation
R_b, is the view factor of the beam
I_d, is diffuse radiation
I_{Pg}, is the albedo radiation

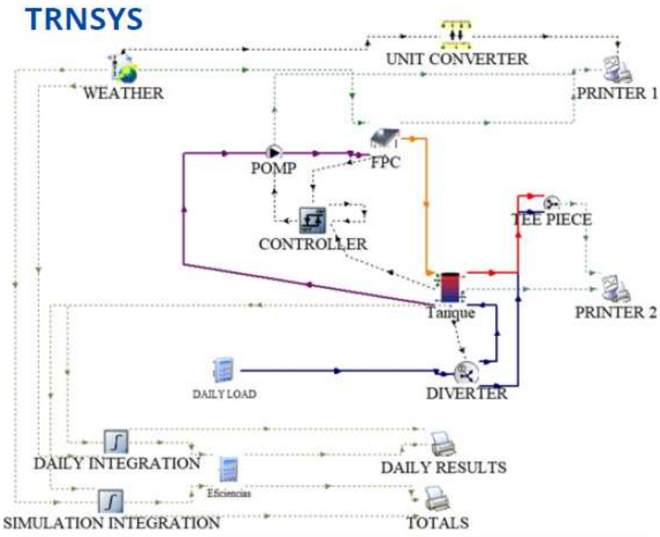

Fig. 2. General model of collectors in TRNSYS

The efficiency of the collector corresponds to the thermal power generated against the incident solar radiation ratio by the irradiation incidence area, the value is usually expressed as a percentage through model (2) [13].

$$\eta = \eta_o - k_1\left(\frac{tm - ta}{I_0}\right) - k_2\left(\frac{(tm-ta)^2}{I_0}\right) * 100 \quad (2)$$

Where,
η, is the efficiency
η_0, is the optical efficiency
tm, is the mean temperature
ta is room temperature
I_0, is the hourly irradiation
k_1, is the linear loss coefficient
k_2, is the squared loss coefficient

The values of optical efficiency and loss coefficients are obtained directly from the solar product catalogue manufacturer, being for the FPC η_o=0.73, k_1=2.51, k_2=0.038, and for the ETC η_o=0.85, k_1=1.47, k_2=0.01. The evaluation was carried out between 6 am and 6 pm. This is due to the fact that before 6 am and after 6 pm the low or null irradiation causes the efficiency results to be negative.

Using TRNSYS, virtual connections were made between the different elements that make up each solar thermal system. The technical specifications of each element were introduced and for the demand input a consumption was established for a family of four inhabitants. In this case, the daily demand for DHW per inhabitant is 50 L (200 L/family) in concordance with the normative [14]. Using a programmable logic controller, the consumption schedules of a house was simulated: three times in the morning, two in the afternoon and two at evening.

Finally, the water flow of 200 L/ day and the inlet water temperature of 15°C has been considered in the simulation process. When simulating the system, the collector output temperatures were obtained. Once the system has been simulated, TRNSYS allows to mark the temperature curves that were obtained as a function of daily hours in both simulations.

3. Results

The validation of the simulation allows comparing the results of the developed models and the real temperature data (ºC). Figure 3 shows both the measured temperature and the simulated temperature, as well as the percentage of error in each hour (for one day) for the FPC01 collector. The average error is 6.27% with a standard deviation of 3.11%, which indicates a low dispersion of the results.

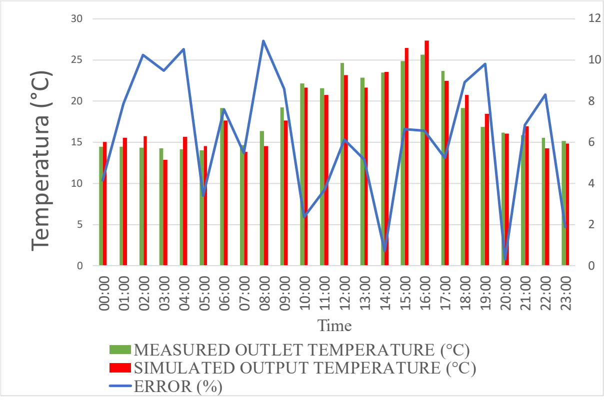

Fig. 3. Measured, simulated temperature and error for collector FPC01

For each system, 4152 readings of the outlet water temperature were obtained throughout one day. With these data, the average errors with respect to the actual collector outlet temperature data were calculated. Similarly, the standard deviation was calculated for the established periods (see Table I).

Table I.- Hourly error and Standard deviation calculated from the FPC01

N° SIM.	COLLECTOR	ERROR	AVERAGE ERROR	SD	AVERAGE SD
1		5.71%		6.69	
2	FPC01	5.77%	5.79%	4.48	5,12
3		5.43%		4.05	
4		6.26%		5.27	
5		6.15%		4.55	
6	FPC02	6.42%	6.20%	5.10	4,85
7		5.54%		4.31	
8		6.67%		5.43	
9		4.60%		3.27	
10	ETC01	6.18%	5.60%	5.59	4,43
11		5.74%		4.23	
12		5.87%		4.62	
13		4.68%		3.84	
14	ETC02	5.44%	5.57%	4.62	4,51
15		5.84%		4.42	
16		6.33%		5.16	

The actual thermal efficiencies of the solar collectors were calculated by applying formula (2). In addition, the results of the efficiencies of the simulations for each period were obtained, with this, the average efficiency of each system could be calculated and it is expressed on Table II.

Table II. - Average thermal efficiencies.

N° SIM.	COLLECTOR	SOLRAD AVERAGE IT (w/m2)	TEMP. COLLECTOR (°C)	TEMP. (°C)	EFFICIENCY (%)	AVERAGE EFFICIENCY (%)
1		246.30	23.85	15.67	52.73	
2	FPC01	289.50	24.23	15.29	53.28	54.09
3		234.11	23.16	16.41	53.79	
4		274.44	24.73	18.51	56.54	
5		246.30	23.68	15.67	54.00	
6	FPC02	289.50	25.06	15.29	50.04	52.94
7		234.11	23.20	16.41	52.83	
8		274.44	24.95	18.51	54.89	
9		246.30	28.19	15.67	61.26	
10	ETC01	289.50	25.52	15.29	66.12	66.58
11		234.11	25.13	16.41	69.16	
12		274.44	26.15	18.51	69.76	
13		246.30	32.21	15.67	57.95	
14	ETC02	289.50	28.28	15.29	63.87	64.86
15		234.11	26.58	16.41	69.05	
16		274.44	28.50	18.51	68.55	

Table III shows the efficiencies of the collectors according to their orientation and slope. It is observed that at a lower inclination angle the performance increase as a consequence of the high solar altitude in the equator an the more direct solar incidence consequently.

Table III.- Variation of efficiency according to orientation and angle of inclination.

N° SIM.	COLLECTOR	INCLINATION	ORIENTATION	AZ (°)	EFFICIENCY (%)
1		14°	East	90	52.73
2	FPC01	45°	North	0	53.28
3		26°	North	0	53.79
4		18°	North	0	56.54
5		14°	North	0	54.00
6	FPC02	45°	East	90	50.04
7		26°	East	90	52.83
8		18°	East	90	54.89
9		14°	South	180	61.26
10	ETC01	45°	South	180	66.12
11		26°	South	180	69.16
12		18°	South	180	69.76
13		14°	West	270	57.95
14	ETC02	45°	West	270	63.87
15		26°	West	270	69.05
16		18°	West	270	68.55

In total, 16 simulations were performed, since four collectors (two FPC and two ETC) were installed, each one operating independently and at different slopes and orientations. In each case, the real results were compared with the simulated results.

Figure 4 show the similarities in the behaviour of the real and simulated temperature values. In particular, the measurements of the ETC collector oriented to the North with a slope angle of **β**= 14 º are shown.

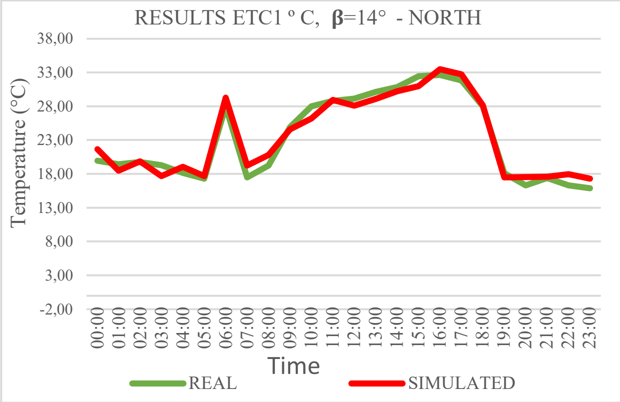

Fig. 4. Comparison of real and simulated temperatures detected in 1 May. 2020.

Using the chi-square goodness-of-fit test, it was determined that the simulated data in TRNSYS fit the same statistical distribution as the measured temperature data as presented on Table V. The thermal heating capability of this systems to heat water reaches as low of 25 ° C to 40 ° C, from 13 ºC as starting temperature, corresponding to local average temperature, then a 56.54% calculated efficiency is reached.

Table V.- Chi-squared Calculation for Simulation 1

CLASS	REAL ABSOLUTE FREQUENCY fo	SIMULATED ABSOLUTE FREQUENCY fe	$\frac{(fo-fe)^2}{fe}$
1	3	6	1.5
2	102	125	4.23
3	600	545	5.55
4	319	353	3.27
5	167	188	2.35
6	294	291	0.03
7	259	245	0.8
8	230	225	0.11
9	95	93	0.04
10	15	13	0.31
11	0	0	0
12	4	4	0
13	0	0	1
	Chi-squared		**18.2**
	Critic value		**21.03**

4. Conclusions

Simulation and validation of solar thermal systems allows uncertainty to be reduced by using simulation tools. In this investigation, four solar collector systems of two different technologies were characterized in different orientations and inclinations of the collectors. The validation between the data obtained and the results of the simulation will allow different scenarios to be analyzed, without the need to install thermal systems that, apart from being expensive, would not allow different working conditions to be proposed.

The validation results show a good correlation between the simulated results and those measured in the built thermal systems. For systems feeded by FPC1, FPC2, ETC1 and ETC2, the calculated errors are 5.79%. 6.20%. 5.60% and 5.59% respectively. According to the chi-square distribution tests, the statistical distribution of the measured values shows a good agreement when comparing with the experimental data obtained in the TRNSYS predictions.

The TRNSYS model allowed to analyze the efficiencies of the systems at different water outlet temperatures. It was established that a system made up of a 2 m^2 FPC and a 200 L storage tank can satisfy approximately 50% of the water demand for a 4-inhabitants house with a overall consumption of 200 L per day. While a system composed of a 3 m^2 ETC and a 300 L storage tank can satisfy around 60% of the energy requirement for DHW. This indicates the energy deficiencies and the complement required thermal requirements from auxiliary systems to maintain temperature requirements for DHW.

Although the solar radiation data are favourable due to the geographical location of the city of Cuenca, the collector efficiencies are limited by climatic factors determined by local cloudiness level. The average ambient temperature in the region ranges between 14°C and 15°C with a clarity index of 0.22, even it has low seasonal variability, most of the year there are diffuse radiation in different level mainly. Then there is a high stability in heat production throughout the year.

References

[1] J. Parreño, L. Oscar, J. Rommel, H. Caicedo, and D. Sarzosa, “Diseño de una módulo de Energía Solar como estrategia de ahorro energético y disminución de la emisión de CO2.,” pp. 4–18, 2020.

[2] M. Vázquez Espí, “Una brevísima historia de la arquitectura solar,” *Por una Arquit. y un Urban. Contemp.*, pp. 1–31, 1999.

[3] S. a. Kalogirou, “Solar thermal collectors and applications,” *Prog. Energy Combust. Sci.*, vol. 30, pp. 231–295, 2004.

[4] R. Madriz and S. Nandwani, “Breve Reseña Histórica de la Primera Asociación Costarricense de Energía Solar (ACES),” vol. 2, pp. 1–9, 2016.

[5] E. A. Barragán, J. L. Espinoza, E. Barragán, and J. L. Espinoza, *Políticas para la promoción de las energías renovables en el Ecuador*, vol. 1. Cuenca, Ecuador, Ecuador: Universidad de Cuenca, Gráficas Hernández, 2015, pp. 1–27.

[6] F. Poggi, A. Firmino, and M. Amado, “Planning renewable energy in rural areas: impacts on occupation and land use,” *Energy*, 2018.

[7] A. Barragán Escandon, “El autoabastecimiento energético en los países en vías de desarrollo en el marco del metabolismo urbano: caso Cuenca, Ecuador,” Universidad de Jaén, 2018.

[8] A. K. Tiwari, S. Gupta, A. K. Joshi, F. Raval, and M. Sojitra, “TRNSYS simulation of flat plate solar collector based water heating system in Indian climatic condition,” *Mater. Today Proc.*, no. xxxx, 2020.

[9] J. Calle-Siguencia and Ó. Tinoco-Gómez, “Obtención de ACS con energía solar en el cantón Cuenca y análisis de la contaminación ambiental Obtaining of SHW with solar energy in the canton cuenca and analysis of environmental pollution,” *Ingenius*, no. 19, pp. 89–101, 2018.

[10] A. Sanchez, “‘ Modelo dinamico con ajuste

experimental de una instalación de colectores solares .,'" 2019.
[11] Solar Energy Laboratory- University of Wisconsin-Madison, TRANSSOLAR Energietechnik GmbH, CSTB - Centre Scientifique et Technique du Bâtiment, and TESS – Thermal Energy Systems Specialists, "TRNSYS 17: A Transient System Simulation Program," 2021. [Online]. Available: https://www.trnsys.com.
[12] B. Y. H. Liu and R. C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse and total solar radiation," *Sol. Energy*, vol. 4, no. 3, pp. 1–19, 1960.
[13] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, Edición: 4. Hoboken: Wiley, 2013.
[14] J. Calle - Sigüencia and O. Tinoco - Gómez, "Obtención de ACS con energía solar en el cantón Cuenca y análisis de la contaminación ambiental," *Ingenius*, no. 19, pp. 89–101, Apr. 2018.