Previsioning Solar Collector Thermal Efficiency from Design Parameters: a Numerical Model Achieved from Test Results

Paulo J. S. Ara[1,2], Daniel S. Sowmy[1,2] and Racine T. A. Prado[2]

[1] Institute for Technological Research, Sao Paulo (Brazil)

[2] Polytechnic School of University of Sao Paulo, Sao Paulo (Brazil)

Abstract

Solar thermal energy has an important role in the current world energetic transition from fossil fuels to renewable energy sources. Solar thermal market enlargement, however, hinges on the enhancement of solar collector thermal efficiency, which, in its turn, strongly depends on collector design parameters such as geometric features, construction quality and design specifications. In this context, the present work aims to obtain a numerical model correlating some collector design parameters to its thermal efficiency for different climatic conditions. The model comprise a set of linear equations, each one for an specific operation and climate condition, using as inputs the absorber plate thickness, number of riser tubes, plate and tube contact type and absorber painting type and providing the thermal efficiency as output for the selected climate and operating condition. For this, a set of 49 thermal efficiency tests results performed on different types of flat plate solar collectors from Brazilian industry was analyzed and correlated with equipment design specifications. The model was validated by submitting an additional collector to experimental test and comparing the experimental result with the predicted one. Validation procedure led to an error lower than 2%. Additionally, using the obtained model, the above mentioned design parameters were ranked according to their influence on thermal efficiency. Results showed that the rank depends on the climate and operation situation. For cold and less sunny operating conditions, painting and tubes are the most important design parameters and for hot and sunny climates, plate thickness and type of contact between plate and tube are more critical. In any case, the efficiency increases as thickness and quantity of tubes increase. Likewise efficiency increases as welding is used instead of fit contact and as selective painting is used instead of standard black painting.

Keywords: Solar Collector, Thermal Efficiency, Design parameters

1. Introduction

Concern about reducing greenhouse gases (GHG) emissions is noticeable in the global energy context. This agenda has been the subject of discussions among countries and organizations so that climate change is mitigated and does not cause the expected damage. The Paris Agreement, proposed in the United Nations Framework Convention on Climate Change in 2015, highlighted the urgent and potentially irreversible threat of climate change, recognized that deep reductions in global emissions are needed, and emphasized the need to limit a rise in temperature to 1.5 ° C above pre-industrial levels (UN, 2015). Despite the relevance of the subject, advances in climate change mitigation have not been enough. Effective reduction of GHG emissions requires a change in the global energy supply, by replacing fossil fuels with renewable energy sources. This renewable transition is already under way, but the current pace is insufficient to achieve the targets proposed by the Paris Agreement, so sectors such as transport, electricity, refrigeration and heating need further progress towards the use of renewable energy sources (REN21, 2018).

According to the REN21 (2018) report, most of the GHG emissions are due to the heating and cooling sector. This sector is also responsible for the largest share of global energy consumption (REN21, 2018). The same report points out that the transition to renewables should cover the following strategies: energy source hybridization, energy efficiency, energy policy alignment at local, regional and national levels, policies focusing on renewable energy through barriers to expansion of fossil fuels and incentives for renewable alternatives

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(REN21, 2018). Recent studies confirm that the transition to renewables is feasible and estimate that in the 2030s the consumption of fossil fuels will peak and then tend to decline (Bond, 2018). In this context, according to IEA (2018), the potential for the use of solar heating is great. In fact, the energy demand of the heating sector (47% of the world total), exceeds the demands of the transport sector (27%) and the electricity sector (17%) (IEA, 2018).

This potential for the solar thermal utilization is not a recent discovery. In fact, the use of solar thermal energy by society began several decades ago. The first records occurred in the third century B.C., in Greece, when several applications used solar concentrators for fire production, including for military purposes. More recently, in the 18th century, solar furnaces appeared for metal casting. In the 19th century, steam engines began to be powered by steam from solar systems. In the 20th century it was observed the expansion of the technology utilization and the construction of larger installations with several applications such as the electricity generation and the activation of pumps and machines. Residential solar heaters only emerged in the 1930s and 1940s, in which simple geometry solar collectors began to be used for ambient heating and domestic hot water production. In the 1960s, the first manufacturers of solar water heaters on an industrial scale emerged (Kalogirou, 2004).

Currently, the thermal utilization of solar energy reaches a considerable scale and according to Simões-Moreira et al. (2017), "solar energy will, in future, represent a considerable part of the energy supply around the world". By the end of 2017, the installed capacity of solar heating systems in the world reached 472 GWth and the energy produced was approximately 390 TWh in the same year (IEA, 2018). At the same time, however, there has been a slowdown in the solar thermal market expansion. According to Weiss and Spörk-Dür (2018), there is a reduction of 9% to 16% in the new introduced solar thermal capacity per year, since 2000. Therefore, in order to exploit the potential of the technology and face these challenges, it is crucial to improve the thermal efficiency of solar heating systems and equipment. Increasing the solar radiation into thermal energy conversion efficiency improves the cost-effectiveness of the technology and also contributes to the suitability of the equipment in product certification programs, both locally and internationally, leveraging the solar thermal market.

Many factors influence solar collector thermal efficiency. They can be classified into three types: environmental factors, installation factors and factors related to solar collector design parameters.

Environmental factors involve the climatic conditions to which the solar collector is subjected. An example of an environmental factor is the incident solar radiation. The radiation level, in turn, depends on the local latitude, on the hour of the day, on the day of the year, on the cloudiness, on the surrounding reflection characteristics, among others. Ambient temperature is another relevant environmental factor. Unlike photovoltaic panels that have their efficiency impaired by temperature rise, for solar collectors, the increase in ambient temperature improves their instantaneous thermal efficiency, as the collector thermal losses are directly related to the difference between absorber plate and ambient temperature. The lower is this difference, the lower will be the thermal losses and greater will be the efficiency. Rainfall and cloudiness are also relevant environmental factors, as they interfere in the thermal conditions to which the collector is subjected.

Factors related to the installation, are linked to the configuration of the solar heating system. Examples are the collector slope relative to the horizontal and its orientation relative to the north. In addition, systems with forced circulation (pumped) or with natural convection (thermosiphon) also operate with different thermal efficiencies. The behavior of other system components such as piping, thermal storage tank and auxiliary heating systems are also factors that interfere with thermal efficiency. Shading is also an important factor related to installation. Especially in urban areas, shading may make not feasible the solar heating system. Another point regarding installation factors is the collector maintenance or degradation, since reducing the transparency of the cover glass caused by dirt or degradation reduces the energy absorbed and affects the thermal efficiency.

Finally, there are factors related to collector design: external area, transparent area, absorber area, geometry of tubes, fins and plate, absorber plate thickness, details and roughness, type of contact between tube and plate, type of cover, type of plate painting, number of tubes, internal and external pipe diameter, air gap, type and thickness of the thermal insulation, among others.

In order to improve thermal efficiency, although it is important to deal with environmental and installation factors, it is convenient to focus efforts on optimizing the design parameters of the collector, which is the subject of this work. In this context, the solar collector must be designed in such a way as to maximize the heat gain by the working fluid and to minimize thermal losses (top, edges and bottom) at the lowest possible cost. Ultimately, according to Jaluria (2008), "the survival of a given product is predominantly a function of its performance per unit of cost".

2. Literature Review

Since the last century, several works have been developed in order to relate solar collector design with thermal efficiency. Abdel-Khalik (1976) studied a solar collector composed of serpentine and correlated, for this case, the heat removal factor (F_R) with collector construction and operating parameters. Theoretical correlation equations were found, so that a serpentine collector may be designed for the desired heat removal factor. The author introduced a set of three dimensionless groups dependent on the collector construction and operation conditions and proposed a serpentine solar collector sizing method using these dimensionless groups. The correlation between the dimensionless groups and F_R was presented in a graph. Conclusion shows that there are ways to improve thermal efficiency (which is related to F_R) for each design configuration, however, there is a maximum value of F_R possible to be reached, for which the possibilities of efficiency increase via design parameters adjustments are exhausted.

Relationships between collector fluid flow characteristics and thermal efficiency were studied by Jones (1987). The author correlated the parameter F_R/F, (being F the fin efficiency factor defined by Duffie and Beckman (2013)) with the modified Peclet number $Pe^* = 3734\,\dot{m}\,/\,(nL)$ where $\dot{m}$ is the manifold flow, n is the number of tubes and L is the riser tube length. Jones (1987) found that, for solar collectors, Pe^* typically ranges from 1 to 25, and identified that there are three predominant flow regimes. For Pe^* from 1 to 4 (low flows), the factor F_R/F increases approximately 20% with as Pe^* number increases, resulting in a significant thermal efficiency improvement. For Pe^* from 4 to 7 it was observed a stabilization of F_R/F around the value of 0.920. For larger flows, corresponding to Pe^* greater than 7, there is no significant thermal efficiency increase as flow rate increases, and the value of F_R/F stabilizes around 0.945.

Norton et al. (1989) studied the relationship between fin geometry and the heat removal factor F_R. As the fluid flows through the collector tubes, fluid temperature rises and the thermal resistance to heat transfer between plate and fluid increases, resulting that fin temperature also increases in the flow direction. From this examination, the authors proposed a triangular shape for the finned plate, reducing fin width in the flow direction. The proposed geometry achieves a heat removal factor of 0.866, greater than the factor of 0.785 which corresponds to the rectangular geometry.

Ghamari and Worth (1992) studied the effect of varying distance between tubes in order to improve the solar collector cost-effectiveness. Theoretically, collector efficiency increases with the reduction of the distance between tubes, however, since the tube usually has a higher manufacturing cost than the plate, there must be an optimal configuration. The authors obtained a model for determining the distance between tubes that optimizes the ratio between the collector efficiency factor (F') and the collector cost, for the cost of materials and manufacturing scenario of the locality in which the work was developed (Suva, Fiji Islands). They obtained that the optimal spacing was 16 cm. An interesting fact of this study is the method used to evaluate collectors with different distances between tubes, without the need to obtain several prototypes for testing. Using strips of different widths glued along the cover glass, the researchers produced shading of specific absorber plate regions. These areas, for thermal effect, are equivalent to vacant areas in the solar collector.

Eisenmann et al. (2004) used the concept of material content to optimize the collector design. In this case, the parameter to be minimized was the ratio between the efficiency factor F' and the collector mass content. This optimization is obtained through variations in fin thickness and distance between tubes. Both of these parameters act to optimize efficiency in an opposite way. The greater the thickness of the fin, the greater will be F', but more material is used. The smaller the distance between tubes, the greater will F', but more material is used. There is, therefore, an optimum point between these two parameters. The authors, thus, obtained relationships between F' and the collector design parameters and proposed a project-oriented abacus that gives the tube-to-tube distance and plate thickness that minimize the amount of mass for a desired value of F' factor. Applying the method, the authors reached a reduction of 20 to 25% in the mass of material, however, they point out that there may be technical limitations for manufacturing any dimension of components, since the industry uses well-defined dimensional patterns.

Badescu (2006) investigated the effect of different climatic conditions on fin design (thickness and width) in order to optimize the collector cost-benefit. The author found out that the optimum design would involve fins of variable dimensions, but this would hamper manufacturing process. Additionally, the author established relationships between thickness and distance between tubes which would be better for hot seasons and cold seasons in terms of thermal energy production. The relationship between the two parameters - thickness and distance between tubes - was shown to be approximately inversely proportional so that a collector of thick and wide fins can be considered equivalent to that of thin and narrow fins. Badescu (2006) also verified the best parameters configuration as a function of the collector operating temperature and concluded that for collectors working at higher temperatures, narrower and thicker fins are preferred.

Ángel et al. (2013) used ANSYS CFX software to analyze two types of solar collector absorber plate configurations. Both collectors were coupled to thermal storage tanks and put into operation without pumping. Also, in both collectors, the tubes operate as the absorber element, one of them with circular section pipes and the other with rectangular section pipes. Singularities in the flow profile of each collector resulted in different thermal efficiencies, and the collector with circular section pipes obtained better performance due to a more uniform flow distribution. The collector with rectangular section tubes presented fluid stagnation regions, with low Reynolds number, harming heat transfer.

Basavanna and Shashishekar (2013) used ANSYS Fluent software to assess the thermal behavior of solar collectors with triangular cross-section tubes from the point of view of water temperature rise. The studied collector had an area of 0.5 m^2 and riser tubes of triangular section in contact with the absorber plate. Results showed that this design option is interesting in terms of energy efficiency. Also the numerical model proposed by the authors, in which only the plate and tubes are considered, describes well the collector performance.

Ekramian et al. (2014) used also CFD simulation to model a flat plate solar collector and investigate the effect of different solar collector configurations on thermal efficiency. The 3D computational domain was simplified using only one tube and taking advantage of the symmetry condition present in the fin. Results showed that thermal efficiency depends largely on the tubes position, under or above the absorber plate, and also showed that tube above plate configuration was more efficient. The authors also present that as the number of vertices of the tube cross section increases, the collector thermal efficiency improves, so that it is concluded that the circular section is ideal.

Elhabishi and Gryzagoridis (2016) studied three different aspect ratios solar collectors integrated with thermal storage tanks. The collector length was the design parameter assessed. For this, each configuration was experimentally tested to determine the energy produced and accumulated in the storage tank. The experimental results showed that the collector of equal sides provided greater thermal energy gain to the hot water reservoir. Additionally, using Buckinghan's Π theorem and the experimental data, the authors obtained a numerical correlation between system pressure drop and dimensionless groups involving design characteristics.

QADER et al. (2019) numerically modeled an air collector with inclined fins applied to increase turbulence and intensify heat transfer. The authors determined the thermohydraulic performance parameter (THPP), which relates the energy gain due to heat transfer and energy loss due to friction. The optimization of THPP as a function of Reynolds Number, slope, fins pitch and length was performed by Surface Response Method (SRM). The authors obtained a value of 1.928 for THPP, better than those resulting from the usual configurations of these collectors and greater than 1, indicating the viability of the solution.

3. Objective

This work aims to obtain a numerical model to estimate solar collector instantaneous thermal efficiency, for different climatic conditions, from the following design parameters: contact type between absorber plate and riser tubes (fitted or welding), absorber plate type of painting (standard black, standard selective or enhanced selective), number of riser tubes and absorber plate thickness. Moreover, this work intends, from the obtained and validated model, to rank the studied parameters according to their influence on thermal efficiency.

4. Method

The method of this work is summarized by the following steps:

- Get a set of 49 efficiency test results performed on solar collectors from Brazilian industry according EN 12975-2:2006 standard
- Compile the design parameters for each tested solar collector
- Determine mathematical correlation between design parameters and efficiency, for each selected climatic condition listed in Tab.1. Mean fluid temperature was considered to be the mean value between inlet and outlet water temperature.

Tab. 1: Selected climatic conditions

Climate Index	Ambient Temperature (°C)	Solar Irradiance (W/m^2)	Mean Fluid Temperature (°C)
1			10
2	20	1000	20
3			30
4			10
5	15	900	20
6			30

The numerical model achieved in this work can be expressed in the form of eq.1, in which the coefficients c_i, 0 to 5, were determined by linear regression. Model output is η_k, which is the simulated efficiency for each climate index k, 1 to 6 described in Tab.1.

$$\eta_k = c_0 + \sum_{i=1}^{5} c_i x_i \qquad \text{(eq. 1)}$$

The variable x_1 is the absorber plate thickness, x_2 is the quantity of tubes, x_3 equals to 0 if plate-tube contact is fitted and equals to 1 for welding, (x_4, x_5) is equal to $(0,0)$ for standard black absorber plate painting, $(1,0)$ for standard selective and $(0,1)$ for enhanced selective absorber coating. The model input parameters are summarized in Tab.2.

Tab. 2: Input model variables

Variable name	Variable value
x_1	absorber plate thickness (mm)
x_2	number of riser tubes
x_3	0 or 1 depending on plate-tube contact type
x_4	0 or 1 depending on absorber painting type
x_5	0 or 1 depending on absorber painting type

- Validate the model. For validation, an additional solar collector (50^{th}) was obtained and its design data were entered into the proposed numerical model. The thermal efficiency obtained from simulation was compared with the thermal efficiency obtained from this solar collector experimental test
- Rank the parameters according their influence in thermal efficiency for each predefined climatic condition.

To rank the parameters, it was used the eq.2 to calculate the relative weight ($W_{i,k}$) of parameter i, 1 to 5, for each climate k, 1 to 6.

$$W_{i,k} = \frac{\eta_k(X_M) - \eta_k(X_{Mi})}{\eta_k(X_M) - \eta_k(X_m)} \qquad \text{(eq. 2)}$$

Where X_M is the vector $[x_1, x_2, x_3, x_4, x_5]$ that maximizes η_k, X_m is the vector $[x_1, x_2, x_3, x_4, x_5]$ that minimizes η_k and X_{Mi} is $[x_1, x_2, x_3, x_4, x_5]$ with only x_i best for η_k and the others worst for η_k. The quantitative parameters, namely x_1 and x_2, were allowed to range 2 standard deviation around mean value.

5. Results

Calculated coefficients of the model are shown in Tab.3. Linear regressions obtained correlation coefficients (R^2) are in the range of 0.44 to 0.63.

Tab. 3: Coefficients of numerical model

k	c_0	c_1	c_2	c_3	c_4	c_5
1	0.5679	0.2164	0.0056	0.0588	0.0013	0.0365
2	0.4867	0.1861	0.0087	0.0482	0.0095	0.0659
3	0.4055	0.1558	0.0118	0.0376	0.0178	0.0954
4	0.6004	0.2286	0.0044	0.0631	-0.0021	0.0247
5	0.5273	0.2013	0.0071	0.0535	0.0054	0.0512
6	0.4542	0.1740	0.0099	0.0440	0.0128	0.0777

Fig.1 shows the simulated versus experimental efficiencies. The dotted line in the graph would represent the perfect model, in which the model predicts exactly the experimental behavior.

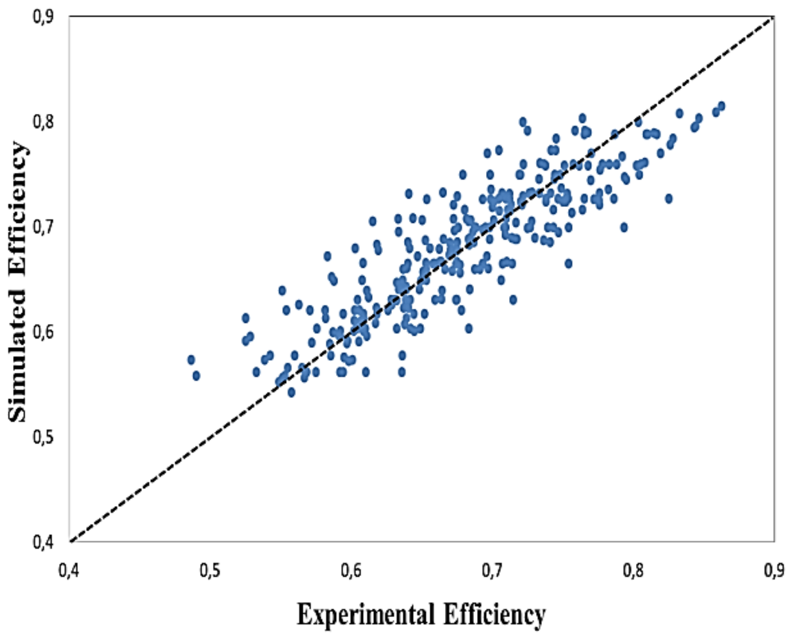

Fig. 1: Simulated versus experimental efficiencies.

In order to validate the model, an additional solar collector with plate thickness of 0,4 mm ($x_1 = 0.4$), 8 tubes ($x_2 = 8$), plate and tube fitted ($x_3 = 0$), standard black painting ($x_4 = 0, x_5 = 0$) was tested and the results were compared to the simulated one. The relative error of the model resulted 1.53% in previsioning this solar collector thermal efficiency.

Ranking results are shown in Fig.2, in which the relative weight ($W_{i,k}$) defined in eq.2 of each studied parameter is illustrated for all climates considered. To represent numerically the climates, each one of them was represented by the reduced mean water temperature (T_m^*) equal to the difference between mean fluid temperature and ambient temperature divided by solar irradiance. As can be seen in Fig.2, parameter relative weight depends on the climate, i.e. there is not an absolute ranking, whereas the importance of a specific parameter depends on the condition in which the collector operates.

A chart for solar collector design purposes was obtained from the results. The chart shown in Fig.3 correlates mean fluid temperature above ambient and solar irradiance. Each region in the chart corresponds to a pair of parameters that lead the rank of importance, to be thought about for design purposes.

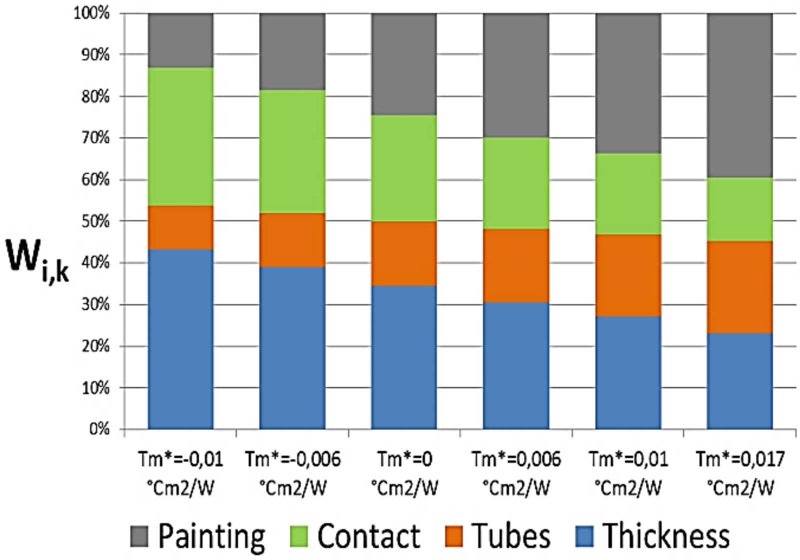

Fig. 2: Relative weight of each parameter.

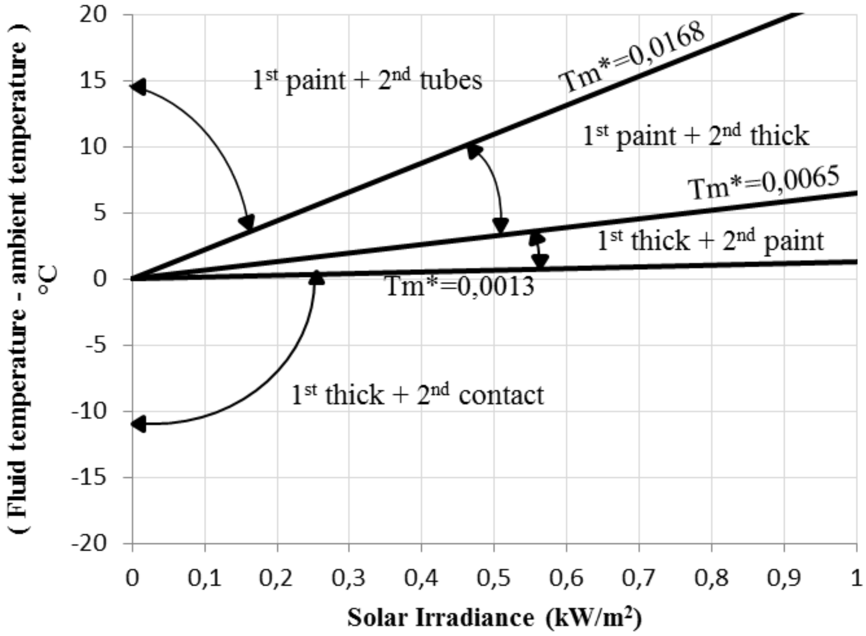

Fig. 3: Design Chart.

For collectors operating at low efficiency conditions (cold and less sunny climates, i.e. high T_m^*), painting and tubes are the most important parameters, explained by the following inferences:

- Absorber painting: small improvement in solar absorption has great potential to improve efficiency as solar radiation is scarce
- Number of tubes/risers: increasing the quantity of tubes reduces plate temperature and thermal losses to ambient air. If ambient temperature is low, thermal losses are important and so this increasing number of tubes is relevant to improve efficiency.

From the chart (Fig.3), the situations above take place for T_m^* higher than $0.0168°Cm^2/W$.

For collector operating at high efficiency conditions (hot and very sunny climates, i.e. low T_m^*), plate thickness and type of contact between plate and tube are the most critical parameters, explained by the following interpretations:

- Plate thickness: thermal energy available in the plate is notable, because thermal losses are low and solar radiation is high. So the critical point is the thermal conduction along the plate which is enhanced by plate thickness
- Contact: there is a lot of thermal energy reaching the tube region from plate, because of low thermal losses and high solar radiation. So the amount of energy reaching the fluid is highly vulnerable to plate and tube contact thermal resistance.

From the chart (Fig.3), the situations above take place for T_m^* lower than $0.0013°Cm^2/W$.

In any case, the efficiency increases as thickness and quantity of tubes increase. Likewise efficiency increases as welding is used instead of fit contact and as selective painting is used instead of standard black painting.

6. Conclusions

The conclusions of the paper can be summarized by the following points:

- A numerical model was proposed to be used as flat plate solar collector thermal efficiency previsioning tool. Model was built from statistical data obtained from tested flat plate solar collectors belonging to Brazil industry
- The introduced model is expressed by a set of linear equations, each one for a specific climate condition, relating solar collector design characteristics with thermal efficiency
- Inputs for the model are the following collector design features: absorber plate thickness (expressed in mm), quantity of riser tubes, type of plate and tube contact (converted to a number by a basic rule), type of absorber painting (converted to a number by a basic rule). Output of the model is the instantaneous thermal efficiency for the selected climate condition
- Model was validated through running the numerical approach for a solar collector previously to experimental test. Test and numerical results deviate 1.53% from each other, considering the mean deviation from all studied climates.
- The proposed model was used to rank thickness, number of tubes, contact and painting according their influence on thermal efficiency
- The importance rank depends on the climate
- For cold and less sunny operating conditions (high T_m^*), painting and tubes are the most important parameters because solar absorption and thermal losses are critical
- For hot and very sunny climates (low T_m^*), plate thickness and type of contact between plate and tube are the most important parameters because heat transfer processes on the plate and tube are crucial.

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8. References

Abdel-Khalik, S.I., 1976. Heat removal factor for fla- plate solar collector with a serpentine tube. Sol. Energy 18, 59–64.

Ángel, M.-D.J., Manuel, O.-R.J., Omar, J.-S., Antonio, Z.-A.M., Armando, E.-O., 2013. Analysis of Flow and Heat Transfer in a Flat Solar Collector with Rectangular and Cylindrical Geometry Using CFD**Chicago citation style Marroquín-De Jesús, Ángel, Juan Manuel Olivares-Ramírez, Omar Jiménez-Sandoval, Marco Antonio Zamora-Antuñano, Armando. Ing. Investig. y Tecnol. 14, 553–561. https://doi.org/10.1016/S1405-7743(13)72265-0

Badescu, V., 2006. Optimum fin geometry in flat plate solar collector systems. Energy Convers. Manag. 47, 2397–2413. https://doi.org/10.1016/j.enconman.2005.11.006

Basavanna, Shashishekar, 2013. CFD analysis of triangular absorber tube of a solar flat plate collector. Int. J. Mech. Eng. Robot. Res. 2, 19–24.

Bond, K., 2018. 2020 Vision: Why you should see peak fossil fuels coming. https://doi.org/10.1002/yd.282

Duffie, J.A., Beckman, W.A., 2013. Design of Photovoltaic Systems, Solar Engineering of Thermal Processes. https://doi.org/10.1002/9781118671603.ch23

Eisenmann, W., Vajen, K., Ackermann, H., 2004. On the correlations between collector efficiency factor and material content of parallel flow flat-plate solar collectors. Sol. Energy 76, 381–387. https://doi.org/10.1016/j.solener.2003.10.005

Ekramian, E., Etemad, S.G., Haghshenasfard, M., 2014. Numerical Analysis of Heat Transfer Performance of Flat Plate Solar Collectors. J. Fluid Flow, Heat Mass Transf. 1. https://doi.org/10.11159/jffhmt.2014.006

Elhabishi, A., Gryzagoridis, J., 2016. Optimizing flat plate solar collector geometry for a solar water heating system. Proc. 24th Conf. Domest. Use Energy, DUE 2016 1–6. https://doi.org/10.1109/DUE.2016.7466719

Ghamari, D.M., Worth, R.A., 1992. The effect of tube spacing on the cost-effectiveness of a flat-plate solar collector. Renew. Energy 2, 603–606.

IEA, 2018. Solar Heat Worldwide, Solar Heating and Cooling Programme Report 2018 - Newsletter v.68. USA - Cedar.

Jaluria, Y., 2008. Design and Optimization of Thermal Systems, 2 nd. ed. CRC Press, Ohio.

Jones, G.F., 1987. Consideration of the heat-removal factor for liquid-cooled flat-plate solar collectors. Sol. Energy 38, 455–458. https://doi.org/10.1016/0038-092X(87)90027-2

Kalogirou, S.A., 2004. Solar thermal collectors and applications, Progress in Energy and Combustion Science. https://doi.org/10.1016/j.pecs.2004.02.001

Norton, B., Hobson, P.A., Probert, S.D., 1989. Heat removal from a triangular finned flat-plate solar-energy collector. Appl. Energy 34, 47–55. https://doi.org/10.1016/0306-2619(89)90054-8

REN21, 2018. Advancing the global renewable energy transition, Highlights of the REN21 Renewables 2018 Global Status Report in perspective. Paris - France.

Simões-Moreira, J.R., Grimoni, J.A.B., Rocha, M. da S., 2017. Energia e Panorâma Energético, in: Energias Renováveis, Geração Distribuída e Eficiência Energética. LTC, São Paulo, p. 420.

UN, 2015. Adoção Do Acordo Paris. Conv. Quadro sobre Mudança do Clima 4, 1–42. https://doi.org/10.1007/s13398-014-0173-7.2

Weiss, W., Spörk-Dür, M., 2018. Solar Heat Worldwide 2018. Global Market Development and Trends in 2017. Detailed Market Figures 2016. IEA Sol. Heat. Cool. Program. 94. https://doi.org/10.1017/CBO9781107415324.004