CFD ANALYSIS FOR INTEGRATED COLLECTOR STORAGE SOLAR WATER HEATERS (ICSSWH) BASED ON CUBOID TYPE GEOMETRIES

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Abstract. *On the last times, renewable energy sources have increasing its participation on the energetic production matrix on all over the world . Solar energy was growing in energy generation using different technologies, highlighting the photovoltaics cells and collection by solar thermal energy. Solar domestic hot water systems (SDHWS) represents an efficient way to decrease the non-renewable energy consumption avoiding the use of fossil fuels and electric energy. The major reported problem of these systems is the high initial cost, despite their lower maintenance cost. To reduce this initial cost, a alternative proposed is integrating solar collector and storage solar water heaters on ICSSWH devices. So, this paper purposes to analyze the general behavior and fluid flux of the ICSSWH during collection and cooling processes to improve and to evolve optimum configuration for high performance. This study was focused on the cuboid ICSSWH models with some structural and parametrical changes. Based on these geometries some project parameters and its influence on the system will be determined. The validation of the model has been done with some results previously presented on the literature. After this, some geometric parameters were modified and new analyses are shown and discussed.*

Keywords*: Solar Energy; integrated collector storage solar water heaters (ICSSWH); Numerical Simulation*

1. INTRODUCTION

The concern for maintaining quality of life on the planet in recent years, was responsible for a strong stimulus in using of renewable energy and created an expectation of an even greater increase in the near future. The use of energy from sunlight reaching the earth's surface represents an important advance in order to contribute to this expectation.

The expansion in use of solar heating on a global scale would reduce the consumption of energy from other sources. In the case of Brazil, specifically, much of this reduction would occur in the consumption of electricity, which is the main source for heating water in the country. Several analysis show that a major obstacle to this expansion is the initial cost of implementing the system and that it could be significantly enhanced if the issue has been outlined. In this context, major studies and new technologies have been developed on the theme. Much information related to these advances can be found in books such as Duffie & Beckman (2006) and Kalogirou (2009).

Based on these considerations, a large volume of recent research related to solar energy has been directed to reducing the deployment costs of the equipment used. Smith, Eames & Norton (2006) show the historical evolution of the system with collector / integrated storage (ICS - Integrated Collector Storage), a alternative way of exploiting solar energy considered for this cost reduction. Although the design of integrated solar collector/storage tank is very old, new schemes of devices have been proposed to improve its performance. An interesting model of an apparatus with these charactheristics was proposed by Kalogirou (1997). Tests performed in this study showed satisfactory results for this model ICS.

Beyond this model, a series of new geometries were proposed for systems with integrated collector and storage tank, highlighting works from Mohamad (1997), Sridhar & Reddy (2007), Gertzos, Pnematikakis & Caouris (2008), Gertzos, Caouris & Panidis (2010), Mondol, Smyth & Zacharopoulos (2011). Different geometries can still be found in reviews as written Smith, Eames & Norton (2006) and Ogueke, Anyanwu & Ekechukwu (2009). In addition to the geometry, another constant concern in this kind of work is to determine the performance or the best method to increase it. In this scope, the amount of information is even greater and could be highlighted some works like: Sopian et al (2004), Hazami et al (2005), Dharuman, Arareki & Srinivasan (2006), Mohsen & Akash (2002), Khalifa & Jabbar (2010), Kumar & Rosen (2010) and Garnier, Muneer & Currie (2011).

Considering the results previously presented and the importance of devices ICSSWH, this study aimed to evaluate the cuboid geometry discussed by Sridhar & Reddy (2007). As the usual geometry has been widely studied and presented inadequate results with regards to thermal stratification in the tank, some changes were proposed. The main changes are related to the internal geometry of the system and can be seen in figure 1 and consist in:

a) geometry using a deflector in output of the collector region to redirect the flow, reducing contact with the cold stream entering in the collector. Moreover, the geometry is proposed in order to redirect the mass flow to the upper region of the collector;

b) evaluate the use of a separator plate in the collector region for separating cold and warm streams, inducing the formation of distinct region for downward and upward flows in the collector;
c) use a combination of two effects proposed in the previous items;

2. METHODOLOGY

A model is developed for a transient simulation for a modified cuboid solar integrated-collector-storage (ICS) system. The proposed has been numerically solved using FLUENT software. A baseline geometry is solved and compared with solutions obtained by Sridhar & Reddy (2007). This results will be used to validate the mesh and the proposed model. After the determination of numerical solution, some enhancements on integrated collector storage tank was proposed to intensify the thermal stratification.

The geometry for this integrated system was composed by a plane region, where the sun radiation is absorbed, and another one where the hot water is stored. The initial and boundary conditions will be imposed for the different regions. The figure 1 shows a scheme for the different systems that are evaluated with geometry details.

For the numerical solution of this problem, one needs to solve the Navier-Stokes equations coupled to the energy equation using FLUENT. The usual form for this proposed set of equations can be seen on Eqs (1) to (5).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\rho\cdot\left(\frac{\partial u}{\partial t}+u\cdot\frac{\partial u}{\partial x}+v\cdot\frac{\partial u}{\partial y}+w\cdot\frac{\partial u}{\partial z}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{\partial P}{\partial x}-[(\rho-\rho_\infty)\cdot g]_x \tag{2}$$

$$\rho\cdot\left(\frac{\partial v}{\partial t}+u\cdot\frac{\partial v}{\partial x}+v\cdot\frac{\partial v}{\partial y}+w\cdot\frac{\partial v}{\partial z}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\frac{\partial P}{\partial y}-[(\rho-\rho_\infty)\cdot g]_y \tag{3}$$

$$\rho\cdot\left(\frac{\partial w}{\partial t}+u\cdot\frac{\partial w}{\partial x}+v\cdot\frac{\partial w}{\partial y}+w\cdot\frac{\partial w}{\partial z}\right)=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{\partial P}{\partial z}-[(\rho-\rho_\infty)\cdot g]_z \tag{4}$$

$$\frac{1}{\alpha}\cdot\left(\frac{\partial T}{\partial t}+u\cdot\frac{\partial T}{\partial x}+v\cdot\frac{\partial T}{\partial y}+w\cdot\frac{\partial T}{\partial z}\right)=\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

The Boussinesq hypothesis was used to considering that there is no change in fluid properties except for the buoyancy terms. By this way, the only change in physical properties that is considerable is density in buoyancy terms. These changes are linearized by the thermal expansion coefficient that is defined as:

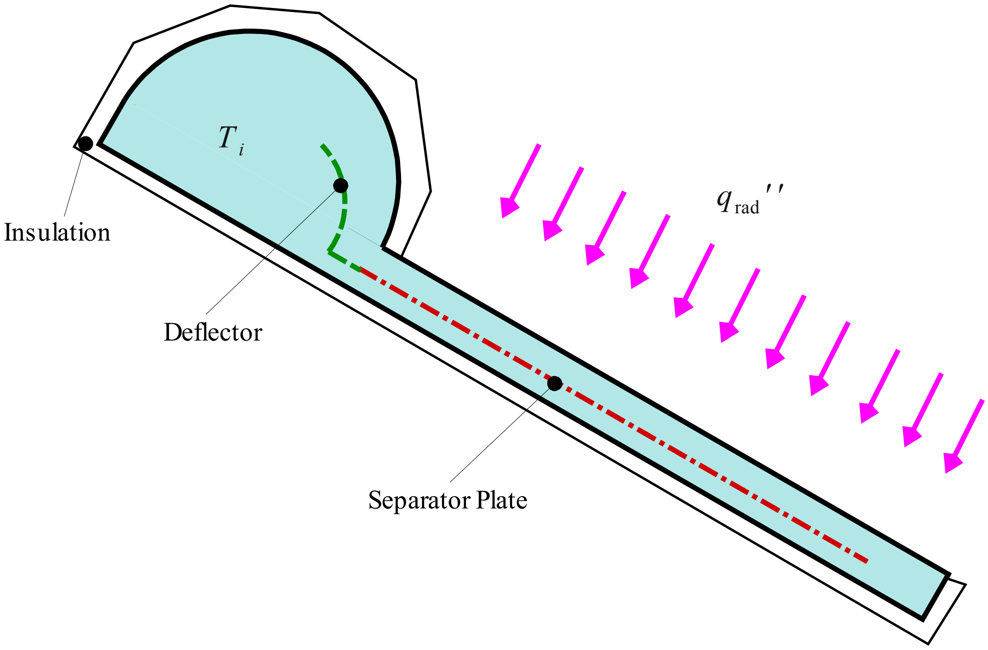


Figure 1: Cuboid scheme including the proposed modifications.

$$\beta=-\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right) \tag{6}$$

which results in:

$$(\rho-\rho_\infty)\approx-\beta\cdot(T-T_\infty)\cdot\rho_\infty$$

that could be used in all directions of momentum expressions that is showed on equations (2) to (4) and is dependent of the body force component on each direction.

The RNG-k-ε model will be used to determinate the turbulence parameters. So, a new set of equations need to implemented. The Eqs (7) and (8) shows the usual form for these parameter that need to be solved coupled with the Eqs (1) to (5) :

$$\rho\cdot\left(\frac{\partial k}{\partial t}+u\cdot\frac{\partial k}{\partial x}+v\cdot\frac{\partial k}{\partial y}+w\cdot\frac{\partial k}{\partial z}\right)=\left(\mu+\frac{\mu_t}{\sigma_k}\right)\cdot\left(\frac{\partial^2 k}{\partial x^2}+\frac{\partial^2 k}{\partial y^2}+\frac{\partial^2 k}{\partial z^2}\right)+P_k-\rho\cdot\varepsilon \tag{7}$$

$$\rho\cdot\left(\frac{\partial \varepsilon}{\partial t}+u\cdot\frac{\partial \varepsilon}{\partial x}+v\cdot\frac{\partial \varepsilon}{\partial y}+w\cdot\frac{\partial \varepsilon}{\partial z}\right)=\left(\mu+\frac{\mu_t}{\sigma_k}\right)\cdot\left(\frac{\partial^2 \varepsilon}{\partial x^2}+\frac{\partial^2 \varepsilon}{\partial y^2}+\frac{\partial^2 \varepsilon}{\partial z^2}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}\cdot P_k-C^*_{2\varepsilon}\frac{\rho\cdot\varepsilon^2}{k} \tag{8}$$

where the parameters can be evaluated by:

$$\mu_t=\rho\cdot C_\mu\frac{k^2}{\varepsilon},\quad C^*_{2\varepsilon}=C_{2\varepsilon}+\frac{C_\mu\cdot\eta^3(1-\eta/\eta_0)}{1+\beta\cdot\eta^3},\quad \eta=S\cdot\frac{k}{\varepsilon}\ \text{e}\quad S=\sqrt{S_i\cdot S_j} \tag{9}$$

and constants used are:

$$C_\mu=0.0845;\ \sigma_k=0.7194;\ \sigma_\varepsilon=0.7194;\ C_{\varepsilon 1}=1.42;\ C_{\varepsilon 2}=1.68;\ \eta_0=4.38\ \text{e}\ \beta=0.012 \tag{10}$$

The software FLUENT used the finite volume method (FVM) to solve simultaneously all the set of equations from (1) to (5), (7) and (8). This software solves conservation governing equations independently in a iterative way and is applicable for this incompressible flow. The solution is based on pressure correction method and uses PISO (pressure-implicit with splitting of operators) algorithm, PRESTO discretization and a second order scheme for the transient solution. The working medium is considered to be water and the effective properties of viscosity and thermal conductivity are taken at temperature 298 K for better comparison with Sridhar & Reddy (2007).

2.1 Boundary Conditions

Considering the boundary conditions, the absorber surface is exposed to a constant heat flux q_{rad}'' and all other ones are considered adiabatic. An initial temperature equal to ambient temperature is adopted for the model. Other condition including convection losses can be used, but changes changes need to be done in parameter conditions. For this case suppose that a general case of heat flux on a surface point ins represented by:

$$q_p''=\gamma\cdot(T_s-\Xi)=h\cdot(T_s-T_\infty)+q''$$

where a general boundary condition represents a condition with heat flux and thermal loses combined.

Manipulating this expression, one can show that:

$$\gamma\cdot T_s-\gamma\cdot\Xi=h\cdot T_s-(h\cdot T_\infty-q'')\ \text{or}\ \gamma\cdot T_s=h\cdot T_s\ \text{and}\ \gamma\cdot\Xi=h\cdot T_\infty-q''$$

Solving this set of equation for a combined condition one can show that:

$$\gamma=h\ \text{and}\ \Xi=T_\infty-\frac{q''}{h}$$

which can be used as a numerically modified boundary condition where the changes in ambient bulk temperature can includes a direct radiation heat flux leaving from the surface. If the heat is incident over the surface the heat flux need a signal change. This condition is adequate when heat flux and convection are present simultaneously on the same surface.

3. RESULTS AND DISCUSSIONS

Prior to obtaining results for changes proposed in device geometry, it was necessary verify the consistency of results. For this purpose, the values were compared with previous results obtained for the usual geometry by Sridhar & Reddy (2007). The comparison was primarily qualitative in nature, but results for maximum temperature on heating stage were compared. These results comparison can be seen on the Figure 3. The good approximation of the maximum temperature values provided, with deviations of about 1ºC between them, shows the good concordance betweeen both models.

Mesh independence study was realized to validate mesh. Results achieved in device with directional are shown in Figure 2 to compare temperature difference between 4 meshes. Computational time from 1.5mm to 3mm was severely reduced by 35%.

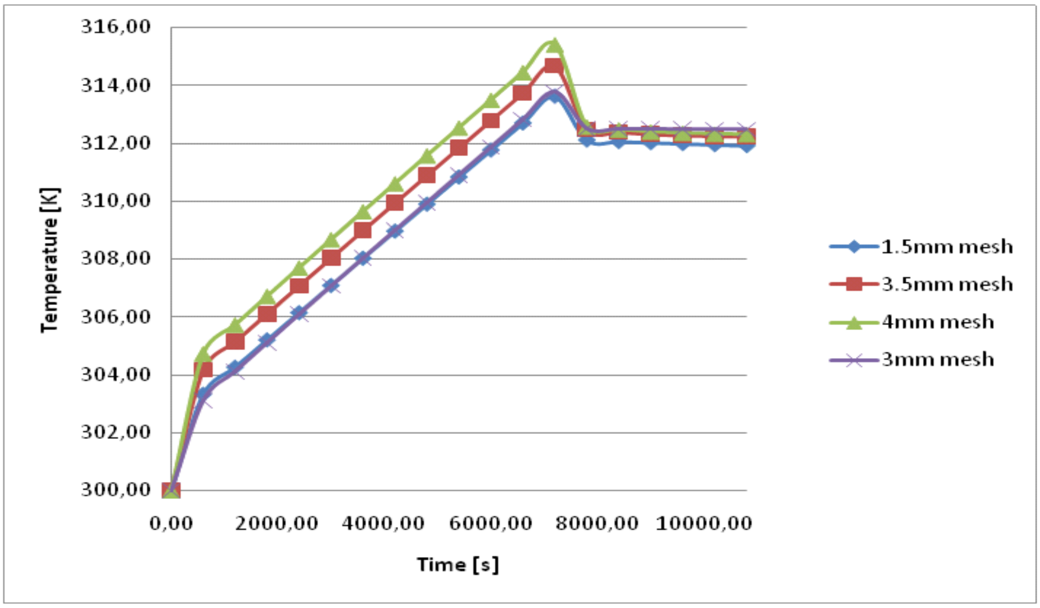


Figure 2: Maximum temperature plot for mesh independence study

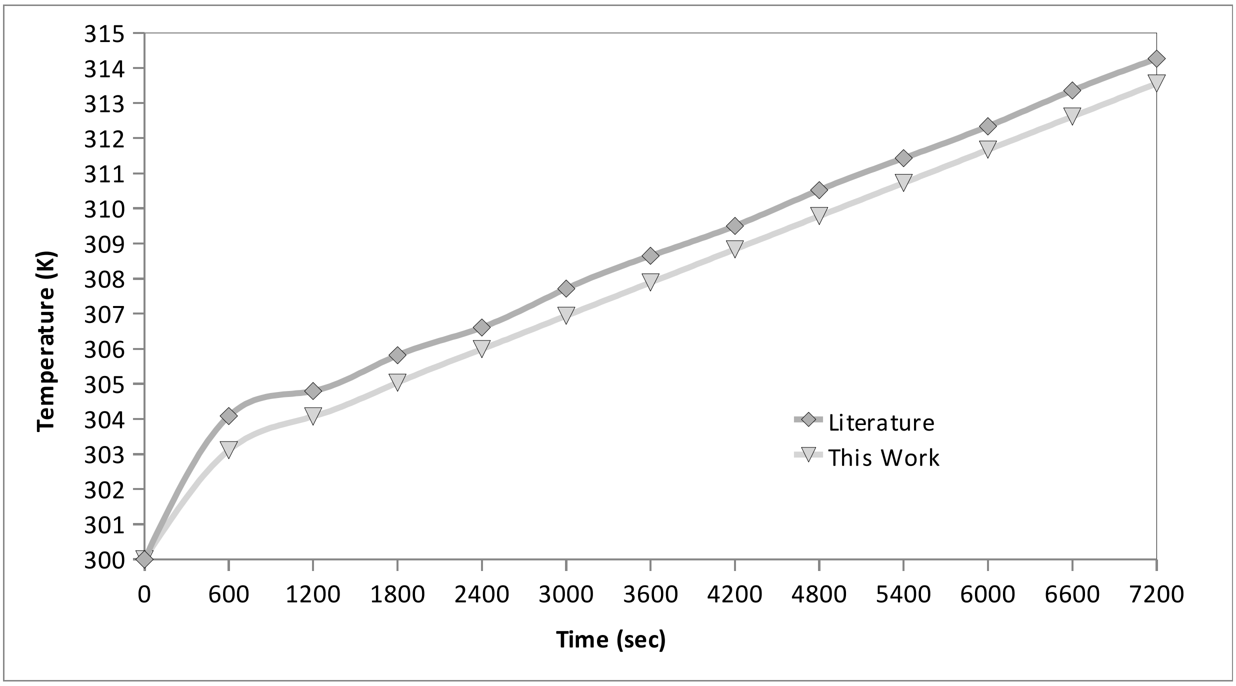
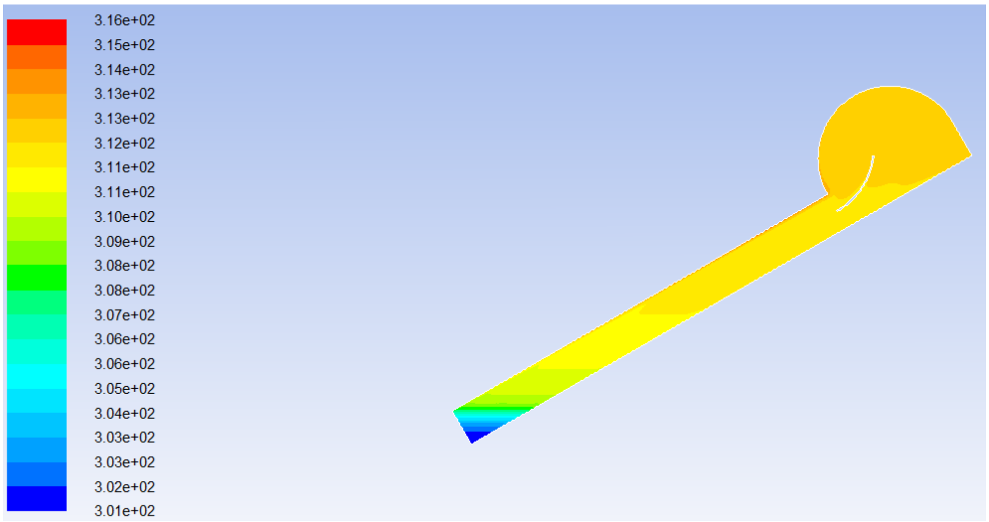
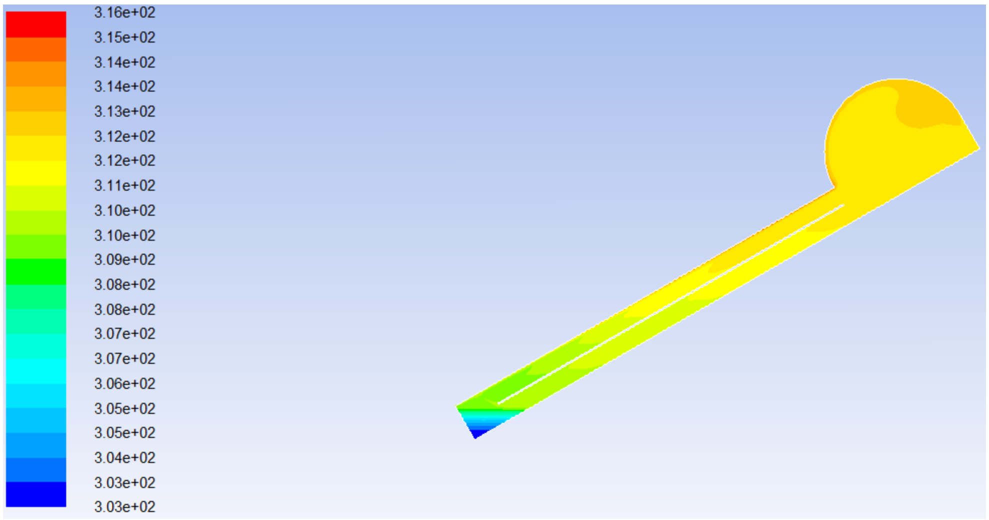


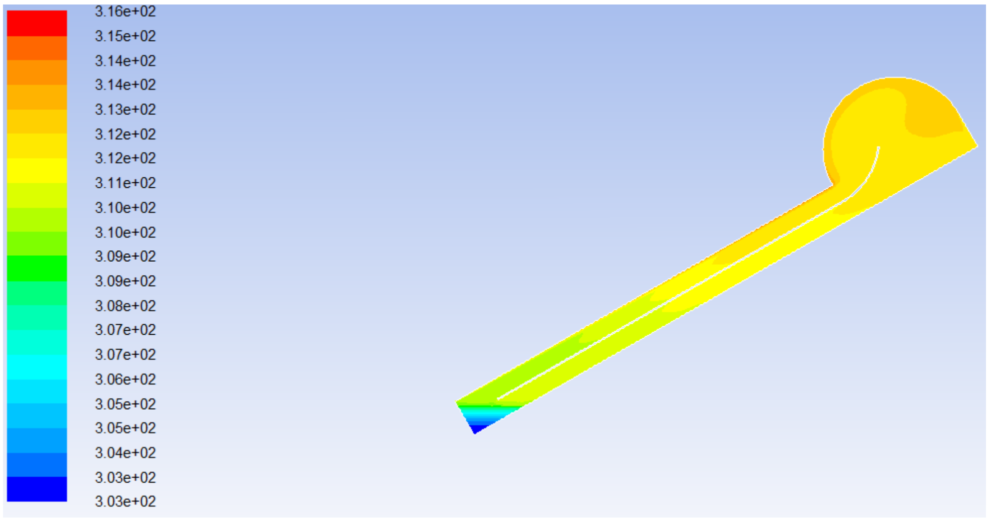
Figure 3: Comparison of results from this work and for literature showed by Sridhar & Reddy (2007).



(a) device with deflector in collector output.

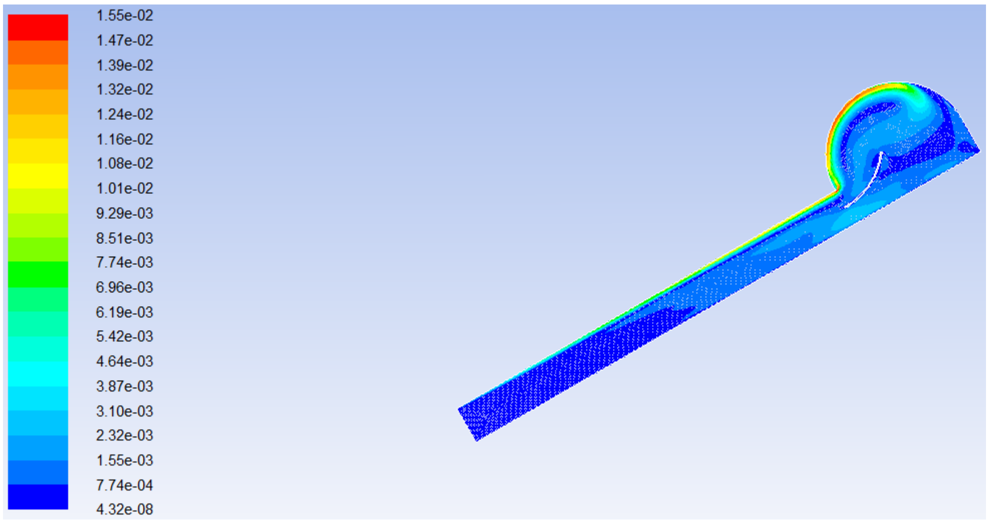


(b) device with separator plate in collector.

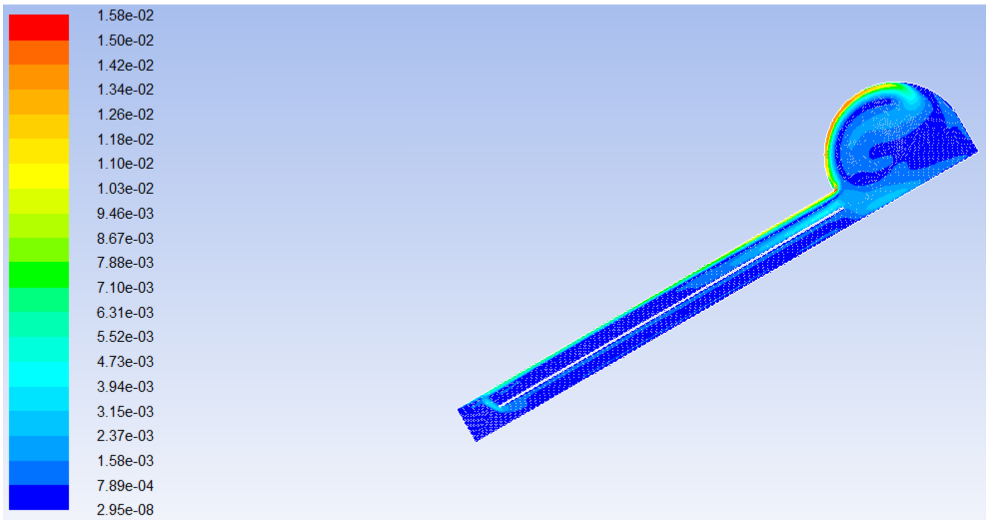


(c) device with separator plate and deflector combined.

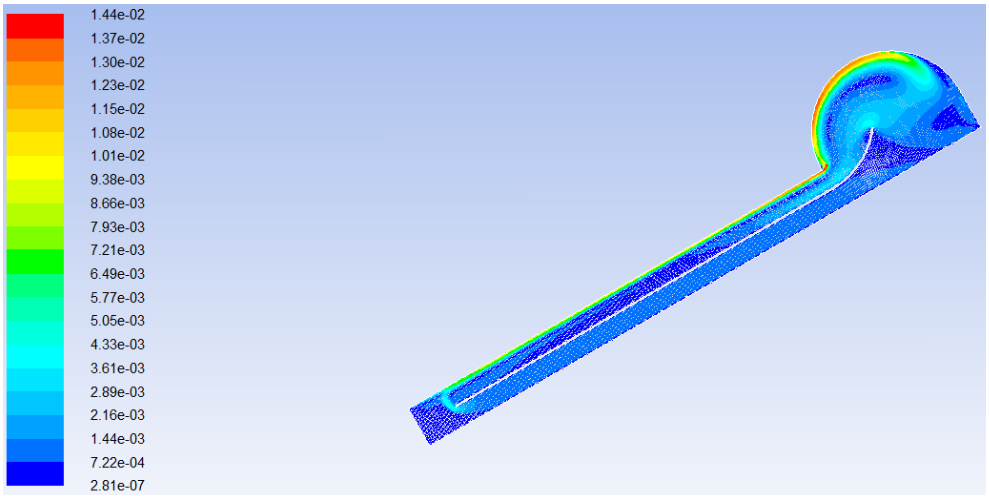
Figure 4: Temperature profile for devices at the end of heating process(t=7200s).



(a) device with deflector in collector output.

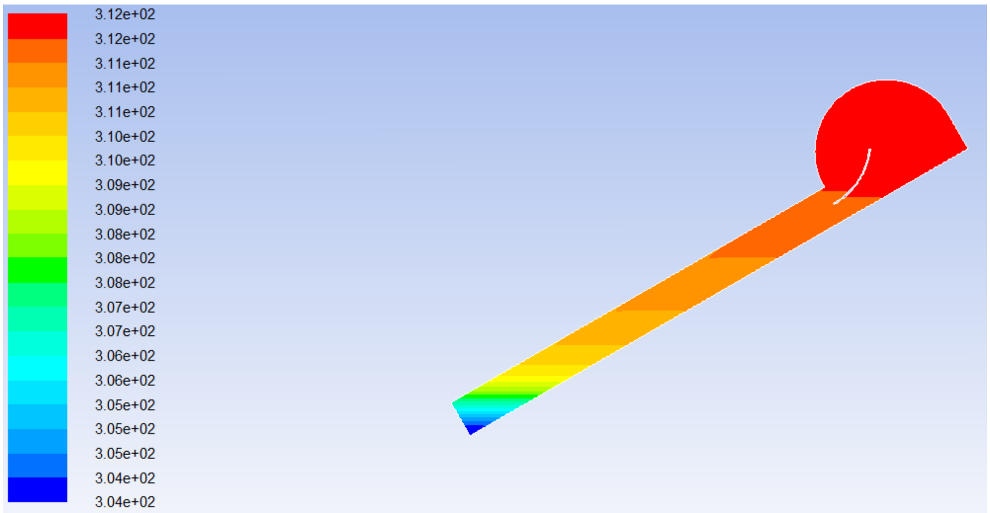


(b) device with separator plate in collector.

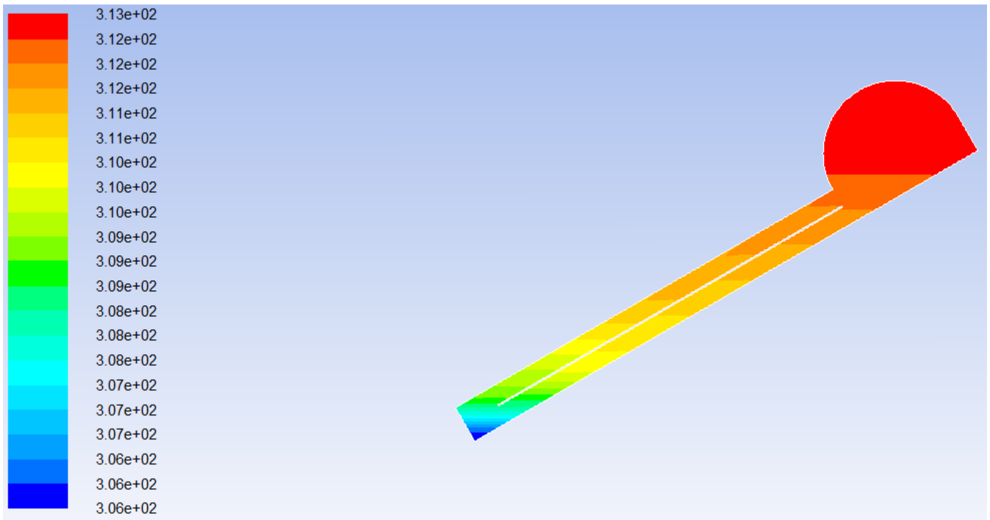


(c) device with separator plate and deflector combined.

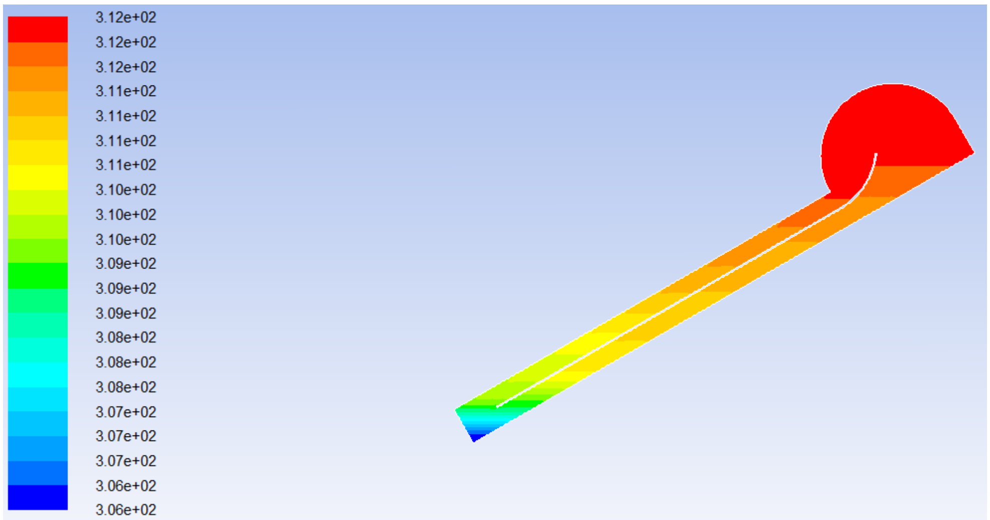
Figure 5: Velocity profile for devices at the end of heating process(t=7200s).



(a) device with deflector in collector output.

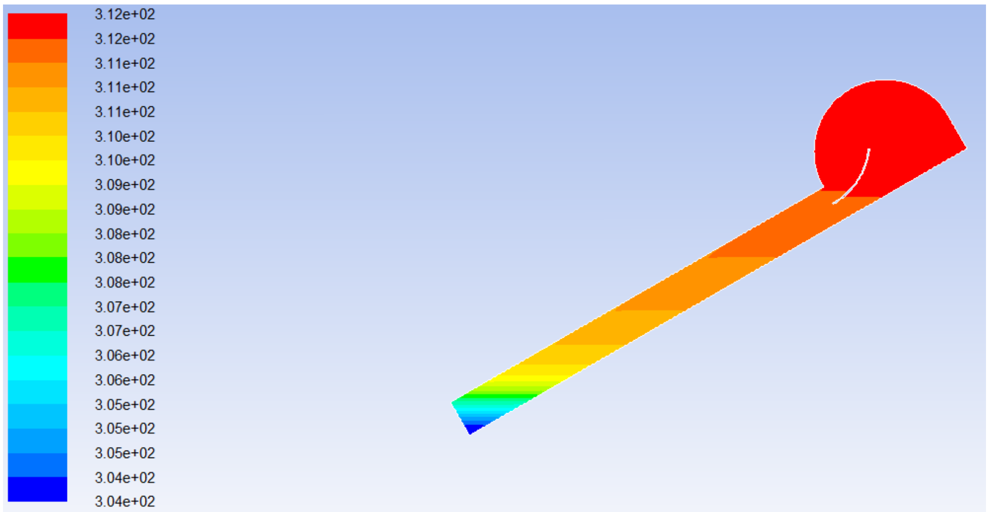


(b) device with separator plate in collector.

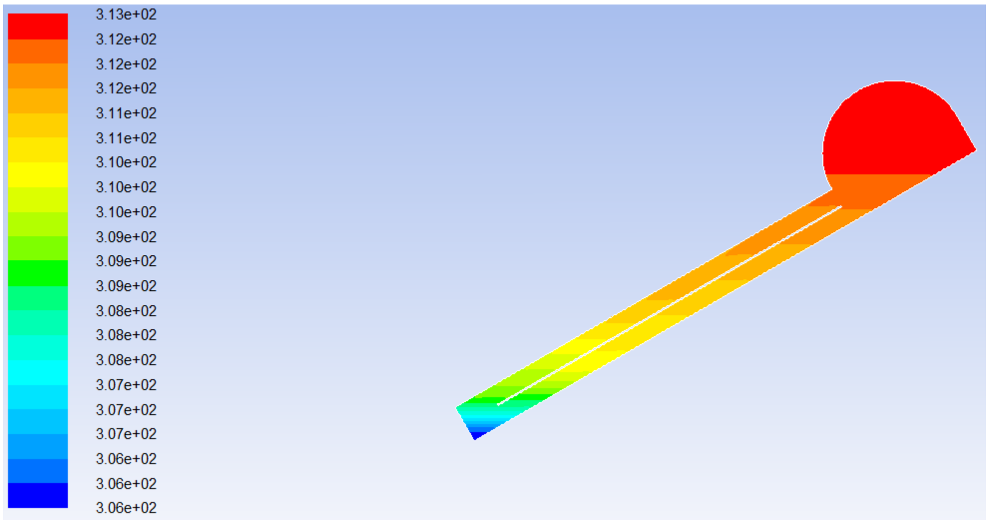


(c) device with separator plate and deflector combined.

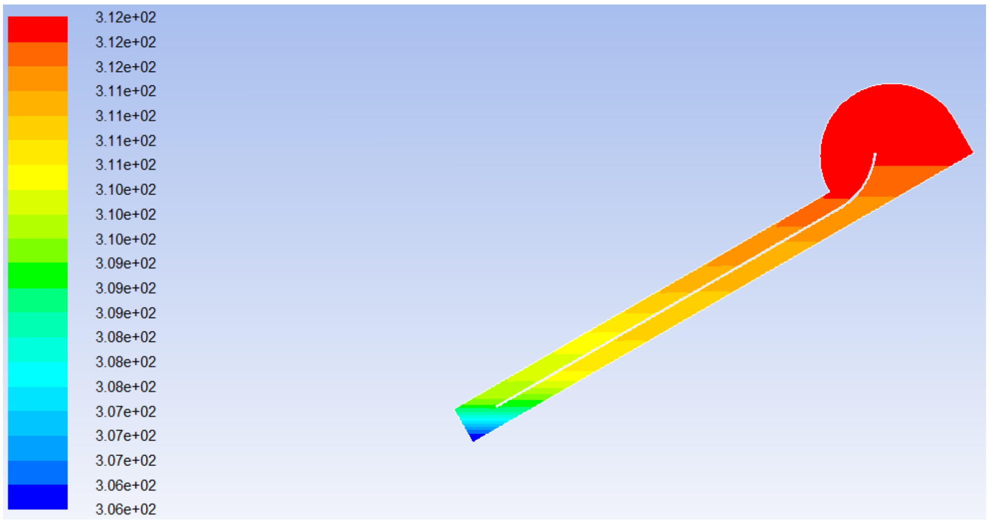
Figure 6: Temperature profile at t=10800s for devices, after the heating(7200s) and at the end of cooling process(3600s).



(a) device with deflector in collector output.



(b) device with separator plate in collector.



(c) device with separator plate and deflector combined.

Figure 7: Temperature profile at t=10800s for devices, after the heating(7200s) and at the end of cooling process(3600s).

In this work it was simulated the behavior of velocity and temperature profile in different previously described geometries. The method for obtaining the solution was also based upon the proposal of Sridhar & Reddy (2007), with a time of 2 hours under a constant heat flux of 950 W / m² one hour and then subjected to a constant heat loss -20 W / m². The conditions at the end of each stage are analyzed and discussed. Although this flow distribution pattern does not represent the phenomenon of heat transfer on the plate during the day, it reduces the computational time required to complete the simulation of the phenomenon allowing to obtain a comparable result for different types of devices. Moreover, the fact that it was simulated conditions for loading during the day and for unloading over the night allow to evaluate the new conditions for development of stratification and temperature profiles.

Figure 4 shows the temperature profile for the previously proposed geometries: with deflector, with separator plate and having both at the end time of 2 hours of heating. The results show that, in all cases, the maximum temperatures are in the region of the collector surface subjected to the flow of direct radiation. Considering the qualitative analysis of stratification must be remembered that in all cases the energy supplied to conjuto was exactly the same and are not considered heat losses to the environment. That said, it can be noted through the temperature profiles that the first situation was most favorable to the layering formation, once it had the highest temperatures in the storage tank. The cases remaining: with plate separator and the two devices, showed very similar results, with a slight advantage in thermal stratification for the case where both devices are included. A justification for this fact was that the flux separator would affect all device, increasing the temperature on the collector base and, consequently, decreasing the maximum temperature and providing a more uniform energy distribution throughout the device.

The velocity profile and its directions for all proposed geometries at the end of the heating stage with time simulated for two hours can be seen in Figure 5. The positions and intensity of the maximum velocities throughout the device after the heating time did not differ significantly among themselves. One can note a slight increase in velocities at the top region of the tank when it's used the system with deflector. The minimum velocities in turn, suffer the biggest changes in their values only when using the separator plate.

Figure 6, in turn, shows the temperature distribution at the end of the cooling step of 1 hour and held just after the heating step. The cooling rate intends to reproduce what happens in real device on the night time. Thus, the value of the rate of heat loss is significantly lower than that received during the loading step. In this analysis, it is interesting to note the great influence of the devices included in the system. The analysis of results allows to notice that the model which was more appropriate was that only uses the separator plate. In this case the maximum values are observed in temperature inside the tank. The use the deflector on the collector output, wich in loading step was advantagous when related to thermal stratification, results in great damage upon the cooling stage. During this stage, the deflector works in reverse, capturing hot water in the upper reservoir and recirculating it. Due to this characteristic, there is a greater temperature uniformity in cases where this geometry change is present.

4. CONCLUSIONS

The analysis shows that the most appropriate modifications to stage of fluid thermal loading is the only use of a driver in the output flow of the collector region. The implementation of this change resulted in a greater water volume at higher temperatures in the reservoir. In contrast, the use of this modification also resulted in a high recirculation when the collector is in the cooling period, implying in a more uniform temperature. Given these characteristics, the implementation of the deflector can bring advantages to the system, but would need accompaniment a system thermal diode, as described by Mohamad (1997). If it is not done, the night recirculation will produce a intense degeneration in the thermal stratification, increased during thermal loading stage. Additional tests can still be done analyzing a reduction in the length of the separator plate and different spacings outputs for cold and hot fluids. Moreover, with respect to the deflector, new designs of its geometry and the use of flow breaks on the surface of the storage tank can also bring performance improvements to the system and need to be tested.

REFERENCES

Dharuman, C., Arakeri, J. & Srinivasan, K., 2006 , "Performance evaluation of an integrated solar water heater as an option for building energy conservation", ENERGY AND BUILDINGS, Vol. 38, pp. 214-219.

Duffie JA & Beckman WA, 2006, "Solar engineering of thermal processes", Wiley.

Garnier, C., Muneer, T. & Currie, J., 2011 , "Thermal model for performance prediction of integrated collector storage systems", JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY, Vol. 3, pp. .

Gertzos, K., Caouris, Y. & Panidis, T., 2010 , "Optimal design and placement of serpentine heat exchangers for indirect heat withdrawal, inside flat plate integrated collector storage solar water heaters (ICSSWH)", Renewable Energy, Vol. 35, pp. 1741-1750.

Gertzos, K., Pnematikakis, S. & Caouris, Y., 2008 , "Experimental and numerical study of heat transfer phenomena, inside a flat-plate integrated collector storage solar water heater (ICSSWH), with indirect heat withdrawal", ENERGY CONVERSION AND MANAGEMENT, Vol. 49, pp. 3104-3115.

Hazami, M., Kooli, S., Lazaar, M., Farhat, A. & Belghith, A., 2005 , "Performance of a solar storage collector", Desalination, Vol. 183, pp. 167-172.

Kalogirou S, 2009, "Solar energy engineering: processes and systems", Academic Press.

Kalogirou, S., 1997 , "Design, construction, performance evaluation and economic analysis of an integrated collector storage system", Renewable Energy, Vol. 12, pp. 179-192.

Khalifa, A. & Jabbar, R., 2010 , "Conventional versus storage domestic solar hot water systems: A comparative performance study", ENERGY CONVERSION AND MANAGEMENT, Vol. 51, pp. 265-270.

Kumar, R. & Rosen, M., 2010 , "Thermal performance of integrated collector storage solar water heater with corrugated absorber surface", APPLIED THERMAL ENGINEERING, Vol. 30, pp. 1764-1768.

Mohamad, A., 1997 , "Integrated solar collector-storage tank system with thermal diode", Solar Energy, Vol. 61, pp. 211-218.

Mohsen, M. & Akash, B., 2002 , "On integrated solar water heating system", INTERNATIONAL COMMUNICATIONS IN HEAT AND MASS TRANSFER, Vol. 29, pp. 135-140.

Mondol, J., Smyth, M. & Zacharopoulos, A., 2011 , "Experimental characterisation of a novel heat exchanger for a solar hot water application under indoor and outdoor conditions", RENEWABLE ENERGY, Vol. 36, pp. 1766-1779.

Ogueke, N., Anyanwu, E. & Ekechukwu, O., 2009 , "A review of solar water heating systems", JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY, Vol. 1, pp. .

Smyth M, Eames P & Norton B, 2006 , "Integrated collector storage solar water heaters", Renewable and Sustainable Energy Reviews, Vol. 10, pp. pp. 503-538.

Sopian, K., Syahri, M., Abdullah, S., Othman, M. & Yatim, B., 2004 , "Performance of a non-metallic unglazed solar water heater with integrated storage system", RENEWABLE ENERGY, Vol. 29, pp. 1421-1430.

Sridhar, A. & Reddy, K., 2007 , "Transient analysis of modified cuboid solar integrated-collector-storage system", APPLIED THERMAL ENGINEERING, Vol. 27, pp. 330-346.

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