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THERMAL-HYDRAULIC OPTIMIZATION OF A SOLAR WATER HEATER THROUGH LONGITUDINAL VORTEX GENERATOR

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Abstract. Nowadays, the development of technologies to harness energy from renewable sources as solar and wind energy has increased a lot, mainly because of concerns about the burning fossil fuel and the fast growth of the populations. The solar energy is a great alternative to meet the increasing demand based on cost effectiveness and accessibility compared to other sources. For thermal solar application, the researchers have been working to enhance the systems to find cheaper process and higher efficiency. These studies are fundamental in order to promote the use of solar energy for, among other, communities with financial restrictions, domestic activities and industry that need of temperature at medium level. The Computational Fluid Dynamic (CFD) and Genetic Algorithm Methodology have been successfully coupled to optimize an objective function problem related to enhancement heat transfer of a solar water heater through Longitudinal Vortex Generators (LVG) which increase the mix between the cold and hot streams near the wall of circular tubes. This passive technique can improve the heat transfer by changing the flow dynamic and delay the detachment of the boundary layer. This work aims to find the optimal shape of a stamped vortex generator over a flat plate inside a circular tube for operating conditions similar those find in Brazil. The parameters of the longitudinal vortex generator evaluated are the angle of attack, height and length which were optimized through Genetic Algorithm approach using a commercial software called by ESTECO ModeFrontier. The heat transfer and the dynamic flow were solved by ANSYS Fluent for Reynolds number 900. The results show the optimal design of LGV which enhance 62% the heat transfer and increase 3 times the pressure drop. The velocity and temperature contours show the mix between the hot and cold streams and the low pressure zones size, besides, the streamlines indicated a corner vortex presence.

Keywords: Solar Water Heater, Numerical Simulation, Longitudinal Vortex Generator, Genetic Algorithm Method.

1 Introduction

Nowadays, the research of renewable sources as solar and wind energy increased a lot, mainly because of concerns about the burning fossil fuel and the fast growth of the primary energy demand, which could rise 3 times by 2050 when the population could be more than 9.7 billion of humans [1], [2]. Best and Burke [3] analyzed the preferences in national adoption of solar and wind energy and found that countries which evaluate the carbon emissions have gone to adopt solar and wind energy systems.

Besides, Kannan and Vakeesan [4] made a discuss about solar industry and the solar energy which could be a great option for future demand based on cost effectiveness and accessibility compared to other sources. In the thermal solar field, some works seek to enhance systems and find cheaper process, better performances and high efficiency. These studies are fundamental to promote the use of solar energy for, among others, communities with financial restrictions, domestic activities and industry, which operate at medium fluid temperature [5].

The research lines of the fluid dynamic and heat transfer optimization have been essential to improve the thermal solar equipment and are present in several similar areas, such as electronics devices, heat exchangers, and automotive industry. The optimization approach Genetic Algorithm has been successfully applied for multi objective function problems in heat exchanges area [6].

The longitudinal vortex generator (LVG) were initially used in aeronautical applications to change the internal and external flow. In this work [7], the authors analyzed the primary vortex generated by a single LVG through the OpenFOAM, this studied was important to improve the aerodynamic performance. In the renewable energy field, the vortex generators have been applied on wind turbines and the results showed that the LVG can improve the aerodynamic performance and decrease the boundary layer thickness [8].

Applied on thermal systems, the LVG could enhance the mix between the cold and hot streams near the wall of circular tubes. This passive technique in order to improve the heat transfer also change the flow dynamic which could delay the detachment of the boundary layer, which could minimize the global pressure drop of the domain [9], [10]. Furthermore, these devices are geometrically simple and could be easy to implement in the industry manufacture process.

This work aims to find the optimal design of a stamped vortex generator over a flat plate inside a tube for a solar water heater operating under a typical residential application. The parameters of angle of attack, height and length of the vortex generator were optimized using the Genetic Algorithm approach to enhance the heat transfer with low pressure drop at Reynolds number 900.

2 Computational methodology

1. Governing equations

Considering an active solar system, the numerical modeling of the heat transfer and fluid flow inside a circular tube is assumed to be three-dimensional and incompressible flow, laminar and steady-state [11]–[14]. For a Newtonian fluid with constant properties, the equations of Continuity, Momentum and Energy are, respectively:

$$\frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\left(\rho u_j u_i - \tau_{ij}\right) = -\frac{\partial p}{\partial x_j} \tag{2}$$

$$\frac{\partial}{\partial x_j}\left(\rho u_j h - k\frac{\partial T}{\partial x_j}\right) = -u_j\frac{\partial p}{\partial x_j} + \tau_{ij}\frac{\partial u_i}{\partial x_j} \tag{3}$$

The computational convergence is ensured for residuals lower than 10^{-4} for Momentum equation and 10^{-7} for Energy equation.

2. Thermal-hydraulic parameters

The water flow inside a circular tube is characterized by the Reynolds number, based on tube diameter, Eq. (4). The parameters to calculate the heat transfer and pressure loss are expressed by the Nusselt number and friction factor, respectively, defined by Eq. (5) and Eq. (6).

$$Re = \frac{\rho u D}{\mu} \tag{4}$$

$$Nu = \frac{hD}{k} \tag{5}$$

$$f = \frac{2\Delta p}{\rho u^2}\frac{D}{L_T} \tag{6}$$

3. Computational domain and boundary conditions

The computational domain was done in the commercial software ANSYS 19.2. Periodic zone is considered, which correspond nearly 0.2 (181.81 mm) of the totally tube length of 1000 mm and 9.52 mm of diameter. This approach allows a high fine mesh hence the results of the convective heat transfer and flow simulations could be better with a practicable computational power and time cost. There are ten vortex generators on flat plate inside the tube, five above and five bellow. Figure 1 shows the periodic zone, the longitudinal vortex generator and the flat plate where the devices were stamped.

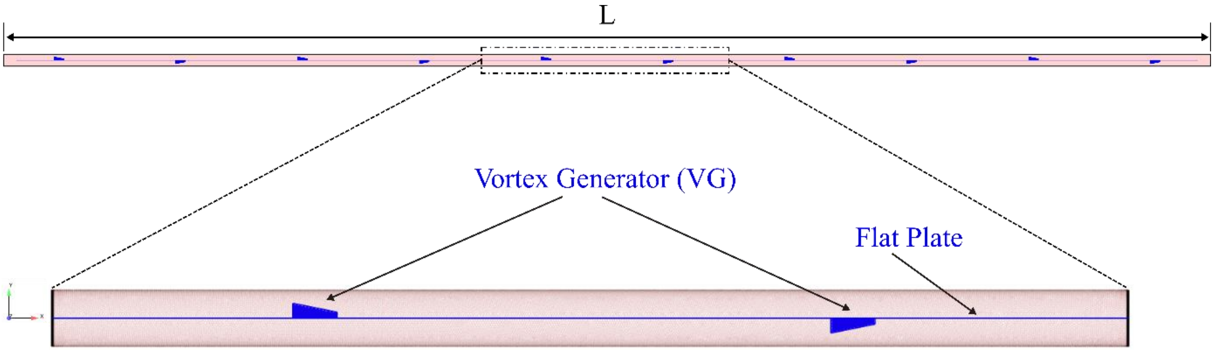


Figure 1. Heat exchanger tube and periodic zone.

Periodic condition in the inlet and outlet is considered of mass flow at Reynolds number 900. The constant heat flux of 750 W/m² is an average value verified for solar radiation in Brazil. Figure 2 shows the boundary conditions and the computational domain used.

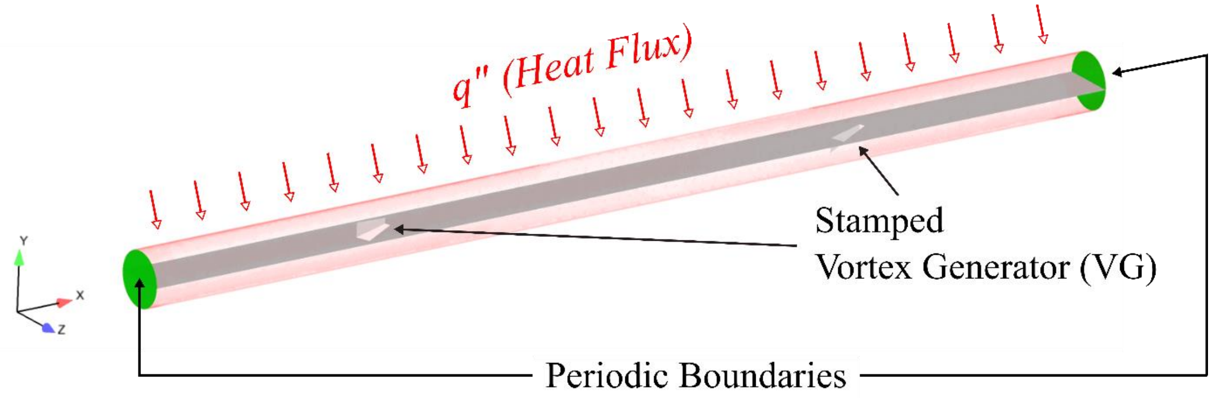


Figure 2. Computational domain and boundary conditions.

4. Grid independence and numerical validation

The grid independence (with vortex generator) was evaluated by Grid Independence Index (GCI) [15]. This method allows to compare the discretization error for different objective function for different mesh densities. *Table 1* shows the three mesh densities evaluated considering the Nusselt number and Friction factor as objective functions.

Table 1. Grid densities evaluated.

	Number of cells	Refinement factor, $r = \left(\frac{G_n}{G_{n+1}}\right)^{\frac{1}{3}}$
Grid 1 (G_1)	854,606	-
Grid 2 (G_2)	1,933,180	1.31
Grid 3 (G_3)	4,208,982	1.30

Division et al. [15] suggest the Refinement factor (r) should be bigger than 1.30 as was done in this work, according to Table 1. It was considered the angle of attack of 45deg in the vortex generators. The discretization error is 2.44% for Nusselt number and 0.10% for Friction factor. Therefore, these low values of error the grid independence is achieved, and the Grid 2 can be used in the numerical simulation of the optimization process. Figure 3 shows the elements of Grid 2 over the tube.

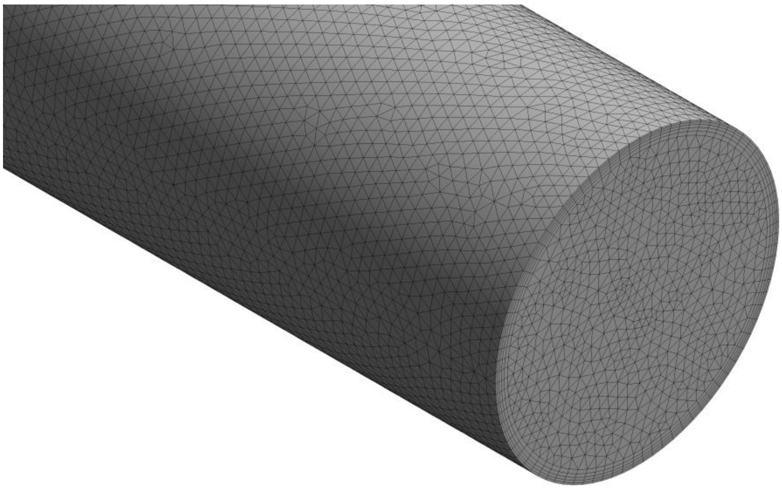


Figure 3. Elements for the Grid 2.

Computational model validation is evaluated through comparison between numerical and theoretical values of Nusselt number and Friction factor. According Incropera et al. [16], the Nusselt number must be 4.36 for a laminar fully developed flow in a circular tube with constant flux on surface, and the Friction factor is given by $f = 64/Re$. In order to ensure the fully developed flow is adopted an iterative process where the outlet velocity profile of the computational domain is set as the inlet velocity in the next iteration. This iteration process is stopped when the thermo-hydraulic parameters is unchanged. Table 2 shows the that the difference between theoretical values and simulation are 1.62% and 1.55% for Nusselt number and Friction factor, respectively, which indicates the numerical approach is reliable.

Table 2. Computational model validation.

Objective function	Theoretical	Simulation	Variation (%)
Nusselt number	4.36	4.43	1.62
Friction factor	0.071	0.070	1.55

3 Optimization process

The optimization problem consists to find the optimal design of vortex generators in order to increase the heat transfer (Nusselt number) with the lower value of pressure drop (fiction factor) associated. The geometric parameters submitted to the optimization process were the both heights (a, b), the length (c) and the angle of attack for the superior and inferior vortex generators. The Figure 4 shows those geometric parameters.

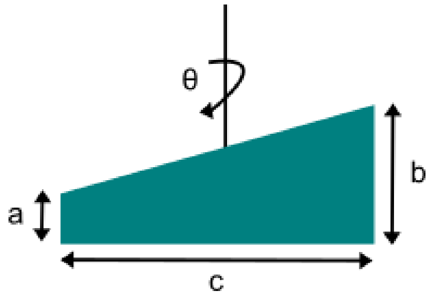


Figure 4. The geometric parameter submitted to optimization procedure.

The ESTECO ModeFrontier is a software multi-disciplinary and multi-objective which allows an easy coupling with the ANSYS 19.2. Those geometric parameters are set for an initial guess in the ESTECO ModeFrontier and the software access ANSYS to adapt the mesh and to solve the flow and the heat transfer. Thus, the thermo-hydraulic parameters can be calculated until the optimization convergence through the Genetic Algorithmic method is reached. Figure 5 shows the graphic interface workflow of the ESTECO ModeFrontier.

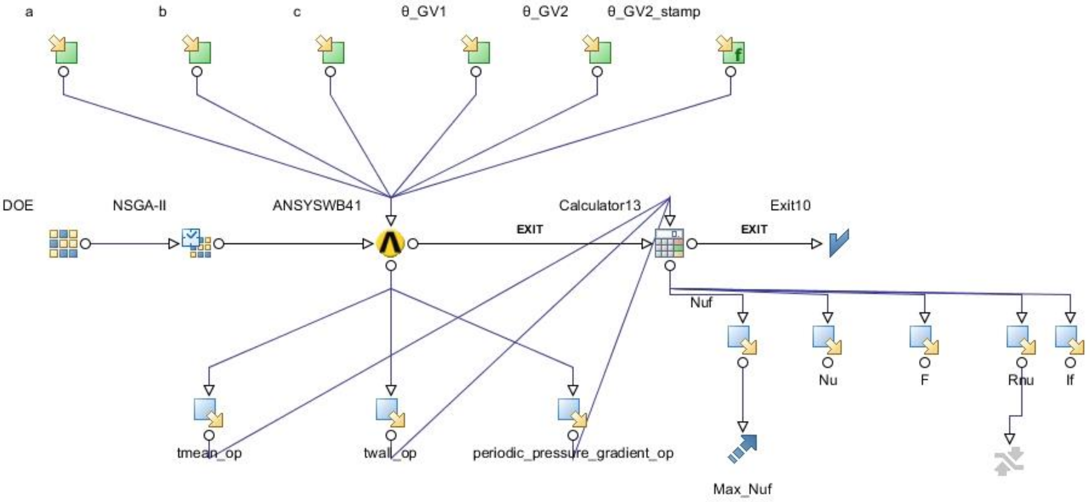


Figure 5. ESTECO ModeFrontier workflow.

4 Results and discussion

The geometric parameters optimization of vortex generators to enhance the heat transfer with low pressure drop associated is performed for Reynolds 900, which represent a typical operating condition of solar water heater. Table 3 shows the optimal values of geometrical parameters of the vortex generator.

Table 3. Optimal geometric parameters values.

Geometric parameters	Values
a	0.9 mm
b	2.5 mm
c	8 mm
θ GV 1	23 deg
θ GV 2	24 deg

The angles of attack of the vortex generator over and below the plate are independent, however, they not show a large variation and indicate that the vortex intensity should keep constant over the entire tube. The Figure 6 shows the optimal design of vortex generator for Reynolds 900.

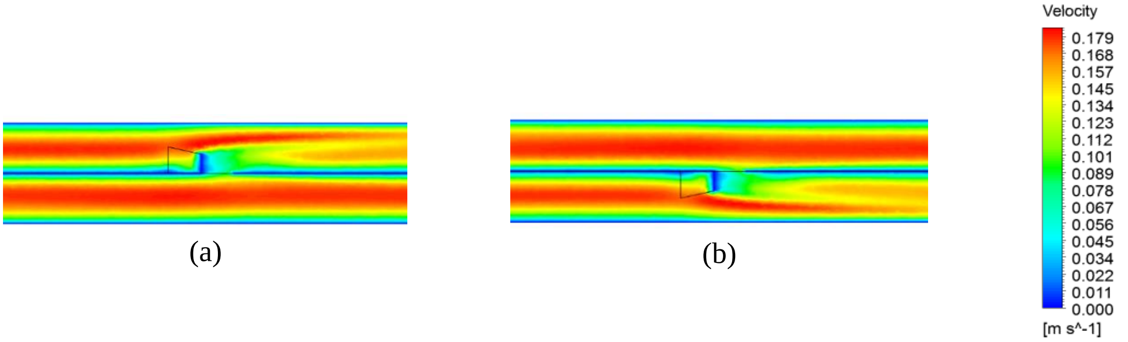
Figure 6. Optimal design of vortex generator.

The shape is similar to a delta-winglet vortex generator, which increase the velocity of the fluid near the wall and enhance the conjugated heat transfer (convection/conduction). The value of the increase in the heat transfer and pressure drop compared with the smooth reference tube can be seen in the Table 4.

Table 4. Increased thermal-hydraulic parameters ratio.

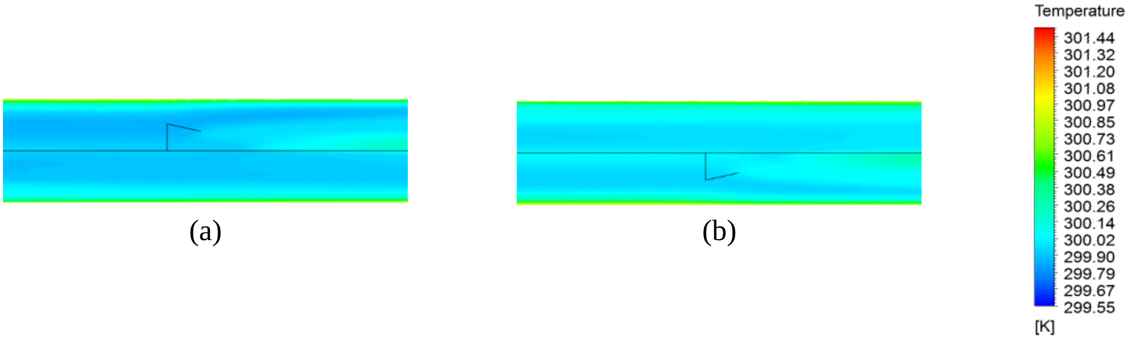
Thermal-hydraulic parameter	Increased ratio
Nusselt number	1.62
Friction factor	3.11

Therefore, the optimal vortex generator enhances 62% the heat transfer, however, the pressure drop associated increased 3 times, indicating a global efficiency of 0.52. This is a good value for a laminar flow and low Reynolds number. Longitudinal planes of velocity and temperature were done and can be seen in the Figure 7 and Figure 8.



(a) (b)

Figure 7. Longitudinal velocity planes (a) VG 1 (b) VG 2.



(a) (b)

Figure 8. Longitudinal temperature planes (a) VG 1 (b) VG 2.

Stamped vortex generators decrease the low-pressure zone behind the devices, Figure 7. This phenomenon is due to the fluid from the underside of the plate flow to the low-pressure zone behind the vortex generator in upper side of the plate, thus the change in the flow corroborates to decrease the pressure drop behind the vortex generators. Figure 8 shows the impact of the vortex generator to mix the cold and hot streams after the generated longitudinal vortex. The flow stream near the wall, with higher temperature, is mixed with the flow stream close to the plate. Figure 9 shows the position of the transversal planes evaluated in the longitudinal direction of the tube (x/L).

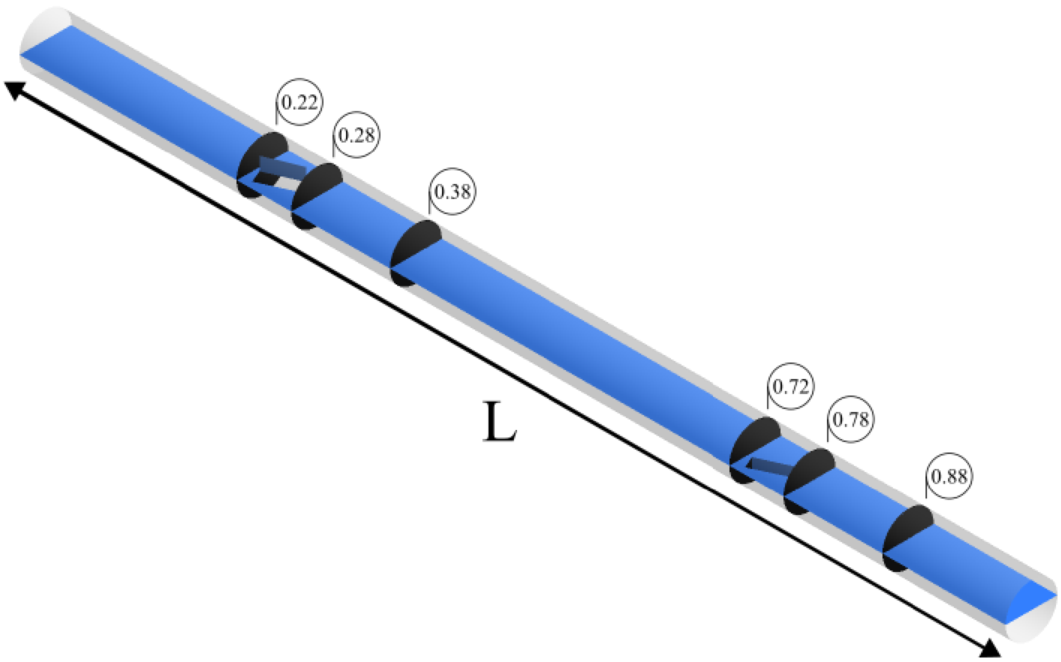


Figure 9. Transversal plans position.

These transversal planes allow evaluating the flow behavior before and after the vortex generators. Figure 10 and Figure 11 show the velocity and temperature contours, respectively, for the smooth tube.

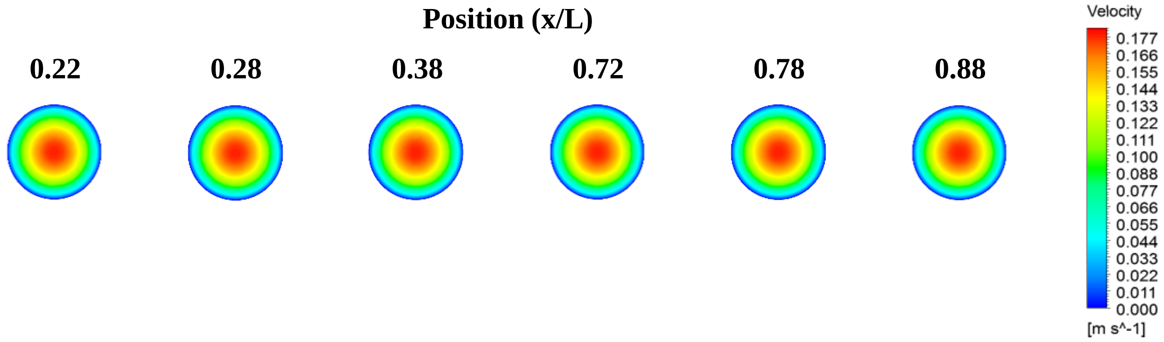


Figure 10. Velocity contours along of the smooth tube.

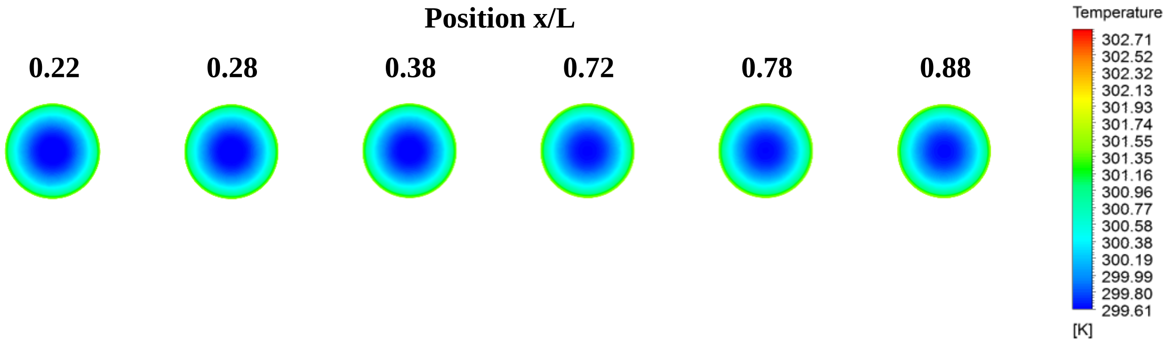


Figure 11. Temperature contours along of the smooth tube.

The mass flow inside the smooth tube has a parabolic profile, with higher velocity in the center of the tube. The temperature of the fluid is higher close to the wall due to the mix of the hot and cold streams. Figure 12 and Figure 13 show the velocity and temperature contours, respectively, for the tube with vortex generators.

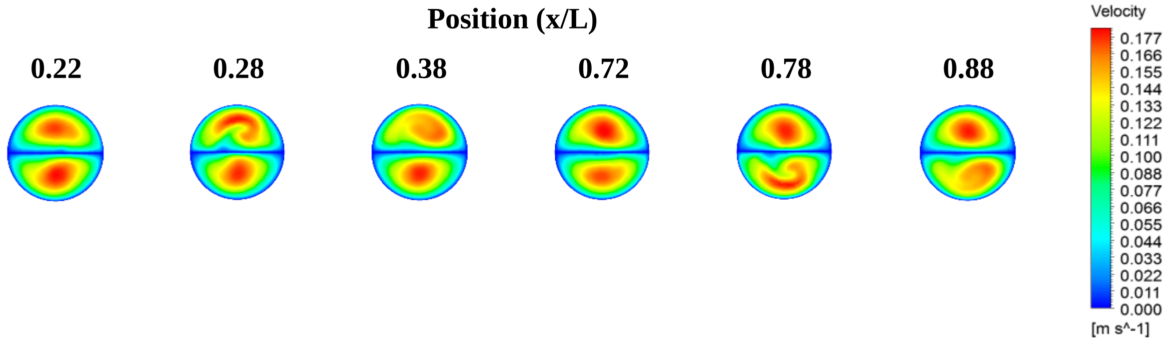


Figure 12. Velocity contours along of tube with vortex generators.

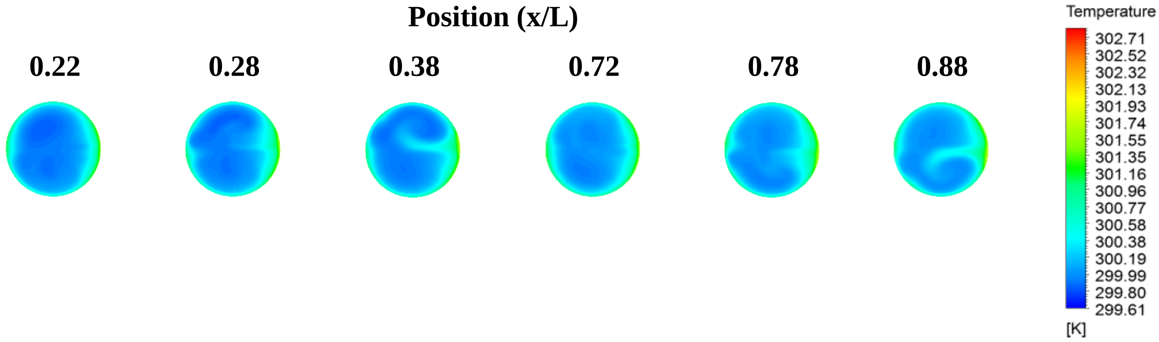


Figure 13. Temperature contours along the tube with vortex generators.

The vortex generator impact on the flow dynamic is evident at position 0.28 and 0.78, according to Figure 9. The devices increase the fluid velocity close to the wall, generating higher distortion in the flow. This modification is due to the creation of a secondary flow toward the longitudinal direction. Therefore, the dynamic and thermal boundary layer thickness decrease, which determine high gradients of property, which increase the convection heat transfer coefficient and, consequently, the pressure drop penalty. Figure 13 shows the mix of the hot and cold streams which is evidenced for the planes at the positions 0.22 and 0.88. Figure 14 shows the streamlines which characterize the vortex at the transversal planes indicated in the Figure 9.

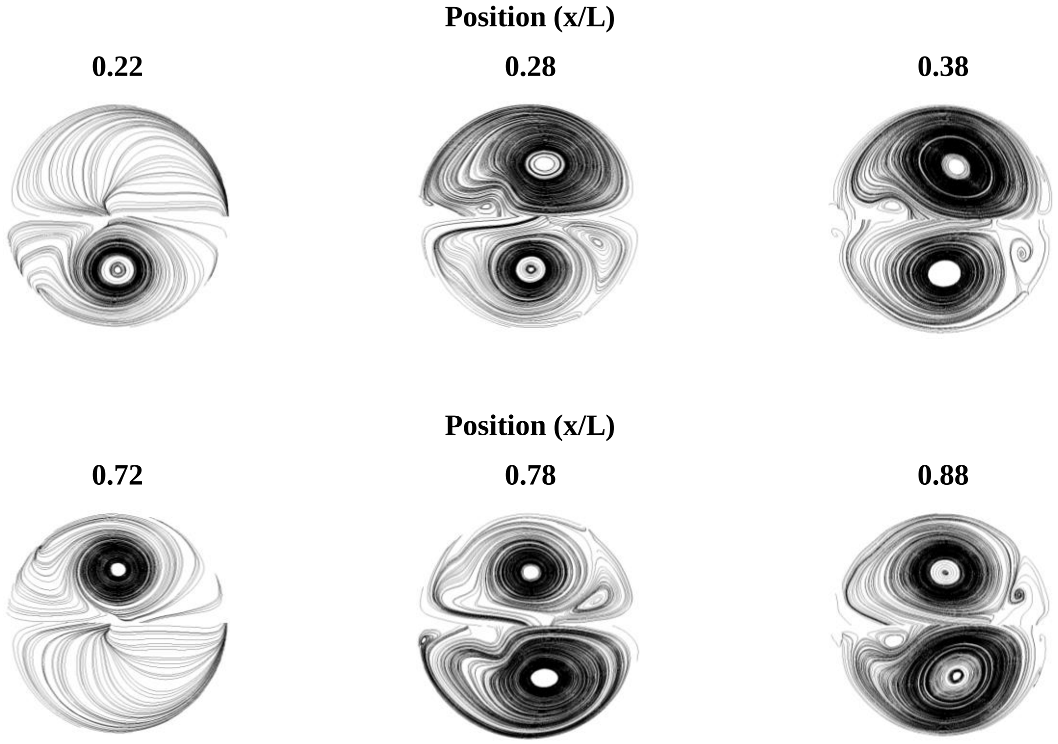


Figure 14. Streamlines along the tube with vortex generators.

The secondary flow is persistent along of the tube, which is verified at the position 0.88, although the distance between the vortex generators is not considered as a parameter in the optimization procedure.

At the positions 0.28 and 0.78, it is possible to see the corner vortex, which is an essential phenomenon to enhance the convective heat transfer, however, the pressure drop associated is also increased.

5 Conclusions

The present work evaluated by optimization procedure the geometric parameters impact on the heat transfer for a solar water heater due to longitudinal vortex generators inserted in a circular tube. The performance of the heat transfer and pressure drop was numerically evaluated through the software ANSYS Fluent 19.2. The optimization with genetic algorithm has been done by the software ESTECO ModeFrontier. The geometric parameters of the vortex generators submitted to the optimization procedure are the both heights (front and rear), the length and the angle of attack. The flow condition investigated correspond to Reynolds number 900, which represent a typical case operation of a Brazilian solar water heater.

The results showed that the application of longitudinal vortex generators to enhance the heat transfer is a promising passive technique, which can increase the Nusselt number of 60%. However, the pressure drop associated is 3 times higher than a smooth tube. Therefore, the global efficiency of this passive technique is 52%.

Through the streamlines is possible to see that the longitudinal vortex is persistent along the entire tube. Besides, the corner vortex is also characterized which contribute to increase the flow distortion. Finally, the results indicate that the longitudinal vortex generator could be successfully applied to enhance the heat transfer for a laminar and incompressible flow.

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