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NUMERICAL SIMULATION OF THERMO-HYDRAULIC PERFORMANCE OF SOLAR AIR HEATER CHANNEL-TYPE WITH PERFORATED DWLS

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Abstract. The present work numerically investigates the effect of perforated area of DWL pairs in common-flow-down arrangements mounted in a solar air heater channel-type on thermo-hydraulic performance of the channel. The flow is considered laminar, steady and incompressible. The three-dimensional numerical simulations are performed by using the Finite Volume Method. The imposed inlet velocity to run the numerical simulations is 0.15737 m/s, corresponding to Reynolds number of 500 (based on the hydraulic diameter). The angle of attack is kept constant and equal to 30º, and the aspect ratio of the DWLs is 1.9. Results show that, depending on the perforated areas, the friction factor decreases about 8% in relation to a standard DWL pair whereas the useful heat gain increases about 3%. Finally, the flow field and heat transfer characteristics are investigated and the main results are discussed.

Keywords: vortex generators, solar air-heater, perforated delta winglets, longitudinal vortices, computational fluid dynamics.

1 Introduction

Energy is a vital resource to life. Due to a growing world population and increasing modernization, global energy demand is projected to more than double during the first half of the twenty-first century and to more triple by end of the century. It is possible to find a close relationship between population increase, economic advance and energy use. As discussed in several studies, while energy demand grows, reserves of non-renewable resources decrease. As a consequence, we can observe the rise of renewable energy sources as well as an increase in technological investment in this sector.

Although the world energy matrix is mostly composed of non-renewable resources, i.e. fossil fuels such as oil, gas and coal, there is a great deal of concern about changing this scenario. Ensuring sustainable and future energy supplies will be the greatest challenge. Nowadays attention has focused on alternative sources such as solar energy as it is available as a green energy source and inexhaustible. Among all the renewable energy source options, one of them, which is viable for Brazil, is the solar energy. As explained by Shahsavari and Akbari [1], the solar energy is zero air pollutant during power generation, reducing considerably the emissions of pollutants in the atmosphere and slowing down the global warming.

One of the ways to convert solar energy into thermal energy is by using thermal solar collectors, which absorb the solar radiation in an absorber plate/tube and transfer it to the working fluid. For this reason, solar air-heaters (SAH) gain importance and are widely used space heating, for example. Several techniques aimed at increasing the thermal efficiency of solar air collectors have been used, in order to increase heat transfer associated with controlled pressure loss using passive heat transfer intensification techniques (Bisht et al. [2], Chamoli et al. [3] and Skullong et al. [4]).

The thermal-hydraulic performance of a solar collector depends on the ability of the working fluid to remove the heat stored by the collectors. In principle, the heat transfer between a fluid and a solid surface is increased by increasing the contact area and/or increasing the heat transfer coefficient. The use of modified surfaces and vortex generators result in increased heat transfer and loss of pressure.

The longitudinal vortex generators (LVGs) enhance the heat transfer by generation of secondary flows, and the LVGs normally increase the heat transfer rate with small pressure losses. This heat transfer characteristics are evident on the review from Jacobi and Shah [5].

In the Figure 1 can be observed a schematic representation of secondary flow created from a typical LVG. As reported in Song et al. [6], the longitudinal vortices significantly improve the heat transfer in steady flow and they present better performance than transverse vortices.

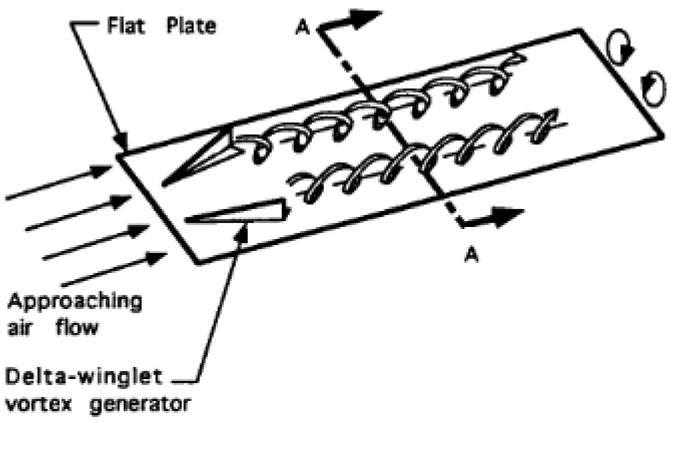

Figure 1. Secondary Vortex generated by DWLs [5]

Fiebig [7] concludes the heat transfer increases with the augmentation of both angle of attack (until 45º) and frontal area of the LVG.

From the literature review about this subject, only few works can be found about perforated LVGs, where the LVGs normally are perforated with circular holes. In this sense, the current work aims to numerically investigate the effect of non-conventional perforated DWL pairs mounted in absorber plate of a solar air heater channel-type, in common-flow-down orientation and under laminar flow conditions.

2 Methodology

The parameters for calculating heat transfer and load loss depend on the type of geometry and flow conditions. The flow conditions are characterized by the Reynolds number (Re_{D_h}), usually based on the hydraulic diameter. The thermo-hydraulic performance can be determined by the Nusselt number (Nu) and friction factor (f), as follows

$$Re_{Dh} = \frac{\rho u_{in} D_h}{\mu} \tag{1}$$

$$Nu = \frac{h D_h}{k} \tag{2}$$

$$f = \frac{1}{2} \frac{\Delta P D_h}{\rho L {u_{in}}^2} \tag{3}$$

in which ρ is the air density, k is the air thermal conductivity, u_{in} is the inlet velocity, D_h is the hydraulic diameter in the channel entrance, μ is the air dynamic viscosity, $\Delta P = P_{in} - P_{out}$ (P_{in} is the averaged air pressure at the domain inlet and P_{out} is the averaged pressure at the domain outlet) and L is the channel length.

The heat transfer coefficient is determined as

$$h = \frac{q}{T_{plate} - T_{air}} \tag{4}$$

in which q is the heat flux, T_{plate} is the temperature of absorber plate and T_{air} is the temperature of air at the inlet of duct.

Moreover, the useful heat gain is calculated as

$$Q_u = h A_t \left(T_{plate} - T_{mean}\right) \tag{5}$$

in which h is the heat transfer coefficient, A_t is the total area (heated plate area plus the delta-winglet area), T_{plate} is the absorber plate temperature and T_{mean} is the average temperature between inlet and outlet.

3 Computational Domain

The dimensions of the computational domain in the flow direction can be seen in Figure 2. The channel is 120 mm wide, 310 mm long and 30 mm high. The computational domain containing the solar air heater channel with DWLs is shown in Figure 3. Heat flow condition is imposed on the absorber plate and the LVGs (the LVGs are attached to the absorber plate), subjected to a constant heat flux of 300W/m². Opposite the absorber plate, the surface is considered adiabatic. Symmetry condition is used on the sides of the entire computational domain. In solid regions the non-slip condition is imposed. At domain entry, called inlet, the prescribed speed condition is imposed; at domain output, called outlet, static pressure is prescribed.

At the inlet domain, it is imposed a constant velocity of 0.15737 m/s considering the Reynolds number of 500. Finally, a monitoring surface of thermo physical properties of the air is added to the computational domain, where_the calculations of heat transfer and pressure loss were performed. The same calculations were performed at the exit of domain to determine the pressure loss and heat transfer between the monitoring surface and the output of domain.

The three geometries of DWL have aspect ratio of 2.0, where the chord and height of the DWLs are 40 mm and 20 mm, respectively.

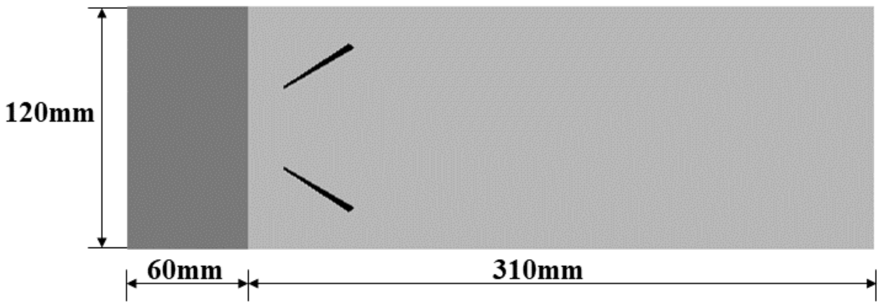

Figure 2. Computational domain

In numerical simulation of incompressible flows, the solution of the system equations is a complicated task since there is a tight coupling between pressure and velocity fields. *Ansys Fluent* has different algorithms; in the *Coupled* algorithm, which is being used in the present project, the mass and momentum conservation equations are solved simultaneously and then the energy equation and other transport equations are solved. The domain is discretized with non-uniform computational meshes, being refined in the regions close to the LVGs and sufficiently coarse in the extensions in order to reduce the computational costs.

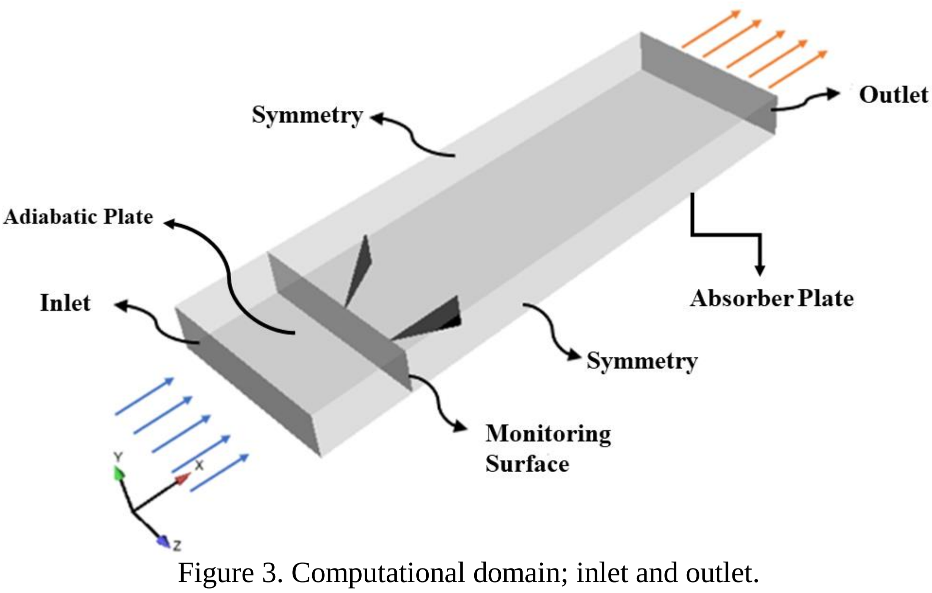

Figure 3. Computational domain; inlet and outlet.

The present research studies the thermo-hydraulic performance of the absorber plate of SAH from three different types of DWLs: standard delta-winglet, perforated delta-winglet with 3mm frame, and perforated delta-winglet with 5mm frame, as shown in Figure 4.

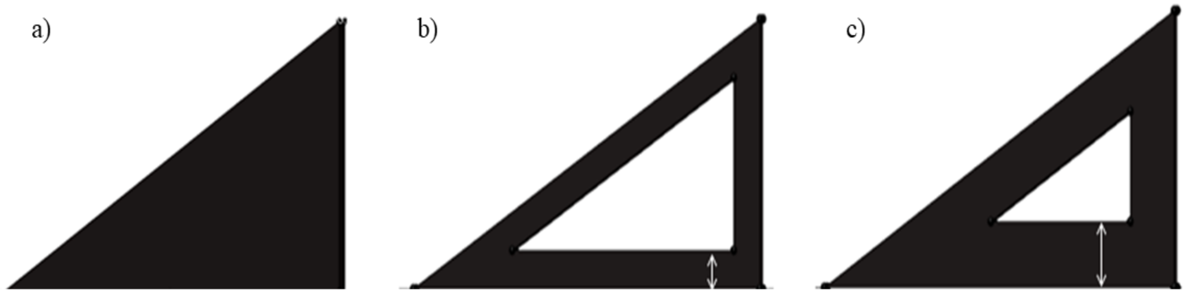

Figure 4. Geometric Modifications: a) Standard DWL; b) Perforated DWL 3mm frame and c) Perforated DWL 5mm frame.

4 Numerical Validation

With regard to the quality of computational discretization (also known as computational meshes) and precision of the results, the independence grid study is performed by using the Grid Convergence Index (GCI) method as reported in Celik et al. [8].

A mesh independence study is performed considering the averaged Nusselt number and friction factor values, where these variables were calculated between the monitoring surface and the main domain output. Three mesh refinements (coarse, intermediate and refined) were chosen according to the criteria required by the GCI method.

As suggested by Celik et al. [8], the GCI method requires a refinement factor greater than 1.3. Consequently, the three meshes were elaborated in order to agree with the mesh refinement factor minimum criterion. For the mesh independence analysis, it was selected a DWL configuration which generated strong longitudinal vortices. In this sense, it was used a standard DWL pair in common-flow-down arrangement with $\theta = 30°$. Table 1 shows the results for friction factor and averaged Nusselt number.

According to Table 1, it is clear that the maximum GCI values for averaged Nusselt number and friction factor were 0.0988% and 0.0000653%, respectively, both at Re = 500. Thus, the intermediate mesh can be considered acceptable for the purposes of the present work since it provides equivalent heat transfer and pressure drop results compared to the refined mesh.

Finally, it is important to emphasize that the quality of the computational meshes generated was constantly verified through the mesh quality criteria (skewness and aspect ratio.).

Table 1. GCI values for the fine mesh

		Fine Mesh	**Intermediate Mesh**	**Coarse Mesh**
Volumes number, **n**		2174285	486428	180514
Mesh refinement factor, **r**			1.64727	1.39156
GCI	$\boldsymbol{f}$		0.0000653%	
	$\boldsymbol{Nu}$		0.0988%	

5 Results and discussions

In the present work was analyzed the useful energy gain, Q_u, and friction factor, *f*, for an absorber plate of a SAH under laminar flow condition.

The Figure 5 presents the temperature profile of the absorber plate (Y = 0 mm). It shows that the strength of the longitudinal vortices from standard DWL pair (Figure 5 (a)) trends to be higher than perforated ones, as observed by the temperature profiles over the plate (the plate temperature is lower in the regions where the longitudinal vortices are created and propagated). In turn, the perforated

DWL pairs (Figure 5(b) and Figure 5 (c)) presents the advantage to decrease the absorber plate temperature at the lateral sides (downstream from DWLs). The vortex structure generated by the standard DWLs is more efficient to mix the hot and cold fluid in the center part of the absorber plate, and not so good enough to promote the heat exchange at the sides of the plate (opposite behavior is observed when perforated winglets are used).

To corroborate with the results discussed above is presented the velocity magnitude at cross sectional planes along the main flow direction for the three different DWL geometries (Figure 6). From that it can be observed the secondary flow from perforated winglets is less persistent along the main flow than the secondary flow from standard DWL pair, as observed in Figure 6. However, the velocity profiles are more homogeneous in perforated DWL pairs than those from standard winglets.

Also, from Figure 6 the flow is accelerated in regions between the DWLs and the velocity of the secondary flow increases along the main flow direction. Moreover, the velocity profiles downstream the DWL pairs are completely different according to DWL geometry.

With regard to Figure 7, which shows the velocity profile at Y = 15 mm, the strength of the main vortex generated at the tip of the standard DWL pair (Figure 7 (a)) is much more intense than that formed by perforated winglets. As the perforated area of the DWLs decreases, the main vortex becomes more intense.

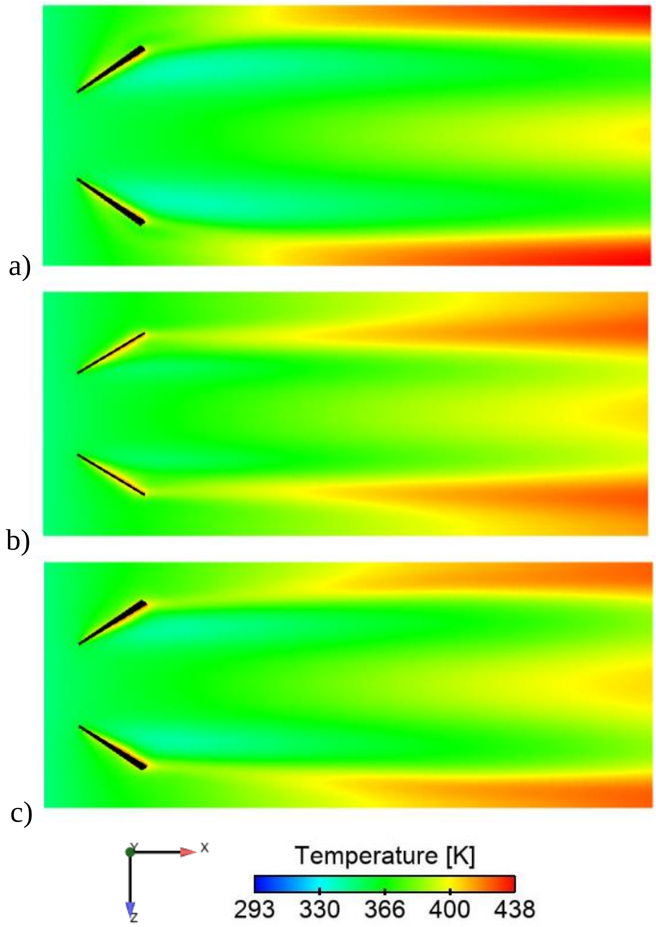

Figure 5. Plate temperature a) Standard DWL b) 3mm frame c) 5mm frame

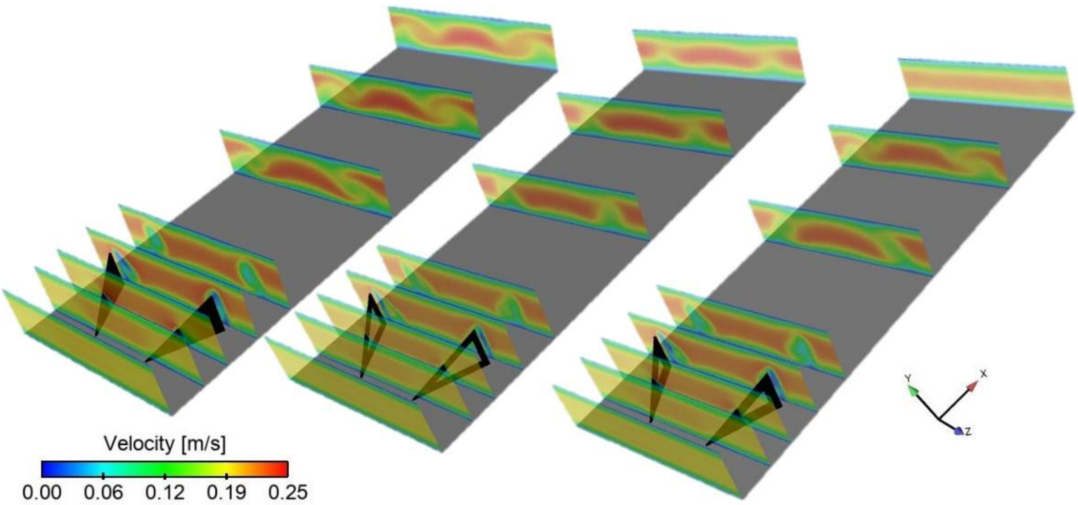

Figure 6. Cross section planes showing the velocity magnitude along the main flow direction for different DWL geometries.

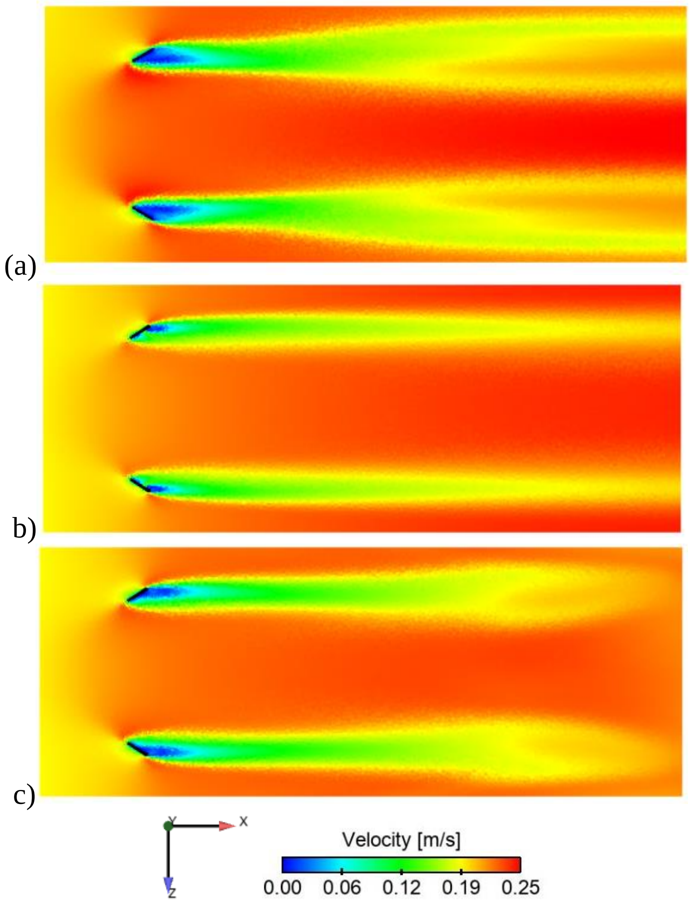

Figure 7. Velocity Plate-to-plate 15mm height a) Standard DWL b) 3mm frame c) 5mm frame

The Figure 8 presents the useful energy gain for the three DWL pairs. The results from DWL pair with 3mm frame showed an increase of 3.97% on Q_u when compared to the standard DWL pair; for the DWL pair with 5mm frame the increase of the useful gain is 1.88% higher than standard DWL pair. Meanwhile, the Figure 9 shows the results from friction factor; it decreased about 8% and 3% for perforated DWL 3mm frame and perforated DWL 5mm frame respectively, in relation to the non-perforated DWL.

From that is possible conclude that perforated DWLs can provide higher thermo-hydraulic performance than the standard winglets, under laminar flow conditions.

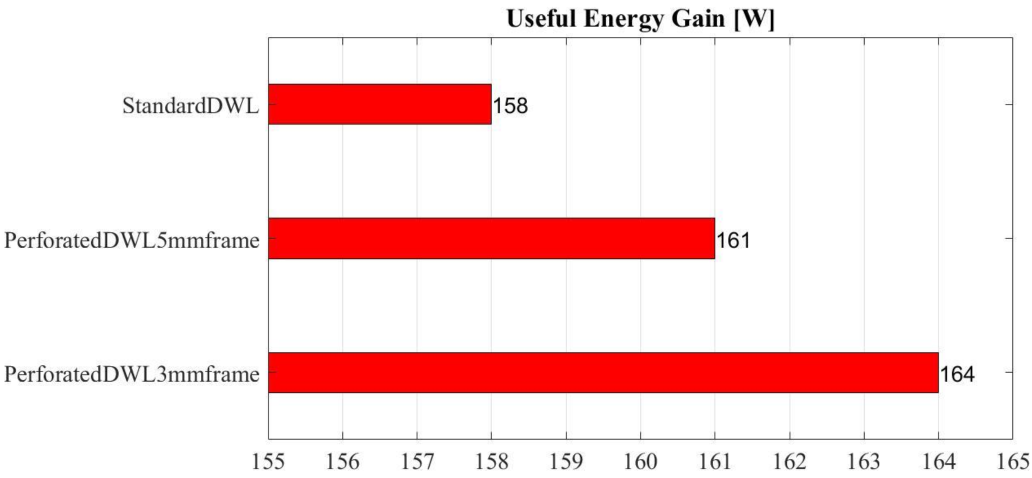

Figure 8. Useful heat gain for the three DWL pair geometries.

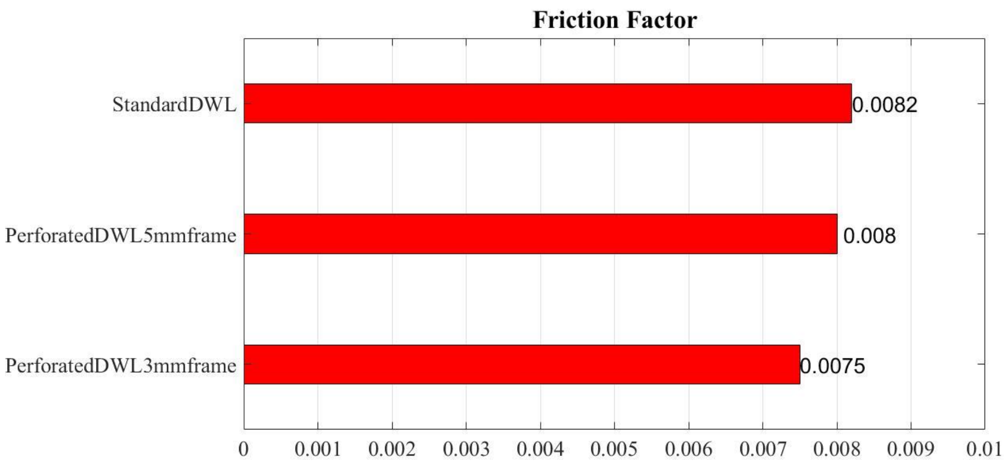

Figure 9. Friction factor for the three DWL pair geometries.

6 Conclusions

The present research studied the heat transfer enhancement and pressure loss for a solar air heater channel-type with standard and perforated delta winglet pairs in common-flow-down orientation. The flow is assumed to be laminar, incompressible and steady. The Reynolds number, based on hydraulic diameter, is kept constant and equal to 500, and the aspect ratio of the DWLs is 2.0 for the three different geometries.

With regard to heat transfer, the results indicated that the perforated winglets perform better than standard winglet. When compared to standard DWL pair, the useful energy gain, Q_u, increased about 4% and 2% for the 3 mm frame DWLs and 5 mm frame DWLs, respectively.

By comparing the results from perforated and standard winglet vortex generators, the associated pressure drop for the 3 mm frame DWL is 8% lower than standard DWLs and for 5 mm frame DWL is 3% lower than standard DWL.

In general, the perforated delta winglets mounted in the absorber plate of a solar air heater presented higher thermo-hydraulic performance than standard winglets, under laminar flow conditions.

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References

[1] Shahsavari, A., Akbari, M. Potential of solar energy in developing countries for reducing energy-related emissions. *Renewable and Sustainable Energy Reviews*, vol. 90, p. 275–291, 2018.

[2] Bisht, V. S.; Patil, A.K.; Gupta, A. Review and performance evaluation of roughened solar air heaters. *Renewable and Sustainable Energy Reviews*, vol. 81, p. 954–977, 2018.

[3] Chamoli, S., Lu, R., Xu, D., Yu, P. Thermal performance improvement of a solar air heater fitted with winglet vortex generators. *Solar Energy*, vol. 159, pp. 966-983, 2018.

[4] Skullong, S., Promthaisong, P., Promvonge, P., Thianpong, C., Pismarn. Thermal performance in solar air heater with perforated-winglet-type vortex generator. Solar Energy, vol. 170, pp. 1101-1117, 2018.

[5] Jacobi, A.M.; R. K. Saha. Heat Transfer Surface Enhancement through the Use of Longitudinal Vortices: A Review of Recent Progress. *Experimental Thermal and Fluid Science*, 1995.

[6] Song, K., Liu, S., Wang, L. Interaction of counter rotating longitudinal vortices and the effect on fluid flow and heat transfer. *International Journal of Heat and Mass Transfer*, vol. 93, p. 349–360, 2016.

[7] Fiebig, M. Vortices, generators and heat transfer. *Chemical Engineering Research and Design*, vol. 76, p. 108–123, 1998.

[8] Celik, I. B., Ghia, U., Roache, P. J., Freitas, C. J., Coleman, H., Raad, P. E. Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications. *Journal of Fluids Engineering*, vol. 130, p. 078001-1–078001-4, 2008.