Heat transfer enhancement using delta-wing streamwise vortex generators

Luciano Garelli, Gustavo Ríos Rodriguez, Mario A. Storti

Centro de Investigación de Métodos Computacionales (CIMEC)-UNL/CONICET
Predio CONICET Santa Fe, Colectora Ruta Nac. 168, Km 472, Paraje El Pozo, Santa Fe (3000), Argentina
lucianogarelli@gmail.com

Abstract.
In this work, a three-dimensional thermo-fluid dynamics simulation using the multiphysics code Code_Saturne is carried out, in order to analyze the performance of delta-wing vortex generators for enhancing the heat exchange in panel type radiators. These radiators are widely used in electric power transformers. The study is focused on natural convection and buoyancy-driven flows, which are common working conditions for this type of heat exchanger. First, the performance of a single delta wing which is placed between parallel vertical plates is analyzed. The best combination of characteristic parameters (aspect ratio, angle of attack) to obtain the highest thermal enhancement factor is established. It is found that separating the vortex generator from the surface of the panel has positive effects in this sense. Then, with the selected configuration, a set of delta-wing arrays is placed on the surface of the heat exchanger and the resulting thermo-fluid dynamics is analyzed. The total heat flux and local / global heat exchange coefficients are reported. Using these passive devices, the overall heat transfer improves by 12%.

Keywords: heat transfer enhancement, vortex generators, panel type radiators, thermo-fluid dynamics simulations, natural convection.

1 Introduction

Vortex generators (VGs) have been widely studied in terms of aerodynamics, as well as heat and mass transfer. Regarding heat exchange enhancement, since 1969 with the work of Johnson [1], extensive research has been performed to understand the improvement in heat exchange and pressure losses produced by VGs. In this study, the influence of several parameters have been considered, such as the angle of attack (AoA), chord length (c), aspect ratio (Λ) and Reynolds number (Re), among others. However, most of the heat exchange enhancement results are for prescribed inlet velocities or fixed Re numbers. In the work of Tiggelbeck [2], a comparison of several types of VGs (delta and rectangular wings, delta and rectangular winglet pairs, etc.) is presented for $2000 < \mathrm{Re} < 9000$ (based on the wing chord length). The wing-type VGs are noted to produce stable and strong vortices, the heat exchange coefficient can increase considerably over an area 100 times greater than the vortex generator area, and winglet-type VGs produce a higher heat transfer, but with a higher friction coefficient, than wing-type VGs. On the other hand, Fiebig [3] found that delta wing VGs are the most effective for heat transfer enhancement per unit area when the results are normalized using the relation between the heated plate and the vortex generator areas. In the context of applying VGs to heat exchangers, the publications [4, 5] investigated the global and local effects of VGs by means of numerical simulations to obtain the thermal enhancement factor (TEF) as defined in Oneissi et al. [4], which considers the increase in the heat exchange coefficient penalized by the increase in the pressure loss, using a prescribed inlet velocity or Re number.

In this numerical study, the focus is done on the usage of VGs in natural convection and buoyancy-driven flows, which are characteristic of panel type heat exchangers, with the objective of increasing heat transfer from the point of view of the air side. Panel type heat exchangers are widely used in electric power transformers wherein the performance is limited by the heat transfer coefficient on the air side.

The work is organized as follows: the numerical model and problem statement are described in the first section. Then, the performance of a single delta-wing VG is analyzed to establish the optimum AoA for typical inlet air velocities ranging from $0.30 \leq \mathrm{u_{in}} \leq 1.05$ [m/s]. These values are obtained from experimental measurements and numerical simulations presented in Rodriguez et al. [6]. Having analyzed the impact of AoA for different air velocities, an additional parameter, the clearance (i.e., the separation between the delta wing and the panel surface), is considered. The separation allows an air passage below the VG that improves the heat exchange coefficient behind the delta wing. Finally, delta wings are placed in an array configuration in the air channel of a radiator panel with a trapezoidal geometry, such as that described in [6], where the air flow is the result of natural convection (i.e., buoyancy-driven flow). The temperature distribution imposed on the radiator panel is obtained from [6], which is more realistic than setting a constant value on the entire panel surface.

2 Numerical Model

The use of vortex generators, particularly delta-wing type generators, introduces a secondary flow consisting of two counter-rotating vortices that propagate streamwise and induce an air flow between them and toward the heated surface. This is denoted as inflow in Fig.(1). The inflow increases the local heat exchange coefficient and reduces the thickness of the fluid dynamic and thermal boundary layers. In the region outside these vortices, the situation is reversed since the hot air coming from the surface toward the bulk of the flow stream, indicated as outflow in Fig.(1), reduces the local heat exchange coefficient and increases the thickness of the fluid dynamic and thermal boundary layers.

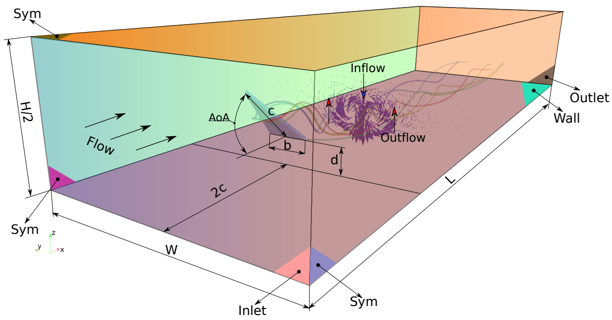

Figure 1. Schematic view - Characteristic parameters of the problem and flow features.

The location of the vortex, combined with its intensity, is fundamental in the heat exchange enhancement, as mentioned in [7]. If the vortex is located far from the boundary layer, the temperature difference across the vortex vanishes, and an advective contribution is not made. On the other hand, if the vortex is located deep in the boundary layer, the size of the vortex is limited by the near-wall surface, and its intensity is not enough to produce a strong inflow / outflow. In between these two extreme scenarios, the optimum location of the vortex is near the edge of the boundary layer, but the interaction between the two counter-rotating vortices makes difficult to maintain that location.

In this numerical study, the local Nu and global $\overline{\mathrm{Nu}}$ numbers will be reported for each analyzed configuration, as well as the TEF and location of the vortex center within the boundary layer for several downstream positions. After selecting the delta wing position that gives the best performance, delta wing arrays are placed in the air channel between two radiator panels to obtain a global TEF for natural convection and buoyancy-driven flows.

At first instance a delta-wing VG is placed between two parallel plates separated by a distance $\mathrm{H} = 40$ [mm] (which is a typical distance between radiator panels in power transformers [6]), of width $\mathrm{W} = 40$ [mm] and length $\mathrm{L} = 127$ [mm]. The wing chord of the VG is $\mathrm{c} = 12.7$ [mm], the wing span $\mathrm{b} = 6.35$ [mm], and the aspect ratio $\Lambda = 2\mathrm{b}/\mathrm{c} = 1$. The trailing edge is placed at $\mathrm{x} = 2\mathrm{c} = 25.4$ [mm] from the inlet. Three different clearance values (i.e., the separation distance from the trailing edge to the heated surface) are considered, $\mathrm{d} = \{0; 3; 5\}$ [mm]. Additionally, three angles of attack are taken into account for each clearance value, namely $AoA = \{30; 40; 50\}$ [deg].

The Re number is calculated using the hydraulic diameter $\mathrm{D_h}$ as characteristic length and the inlet air velocity, $\mathrm{u_{in}}$ as reference velocity.

Additionally, a reference value $\mathrm{T_0} = 303$ [K] is taken for the temperature, then the reference air density and dynamic viscosity are $\rho_0 = 1.17$ $[\mathrm{kg/m^3}]$ and $\mu = 1.86 \cdot 10^{-5}$ $[\mathrm{Pa \cdot s}]$, respectively. The Re numbers for the air velocities considered are $1519 \leq \mathrm{Re} \leq 5316$.

In this study, the air flow is assumed to be stationary and three dimensional, and the fluid is Newtonian. The Reynolds-Averaged Navier-Stokes (RANS) equations govern the motion of the fluid. Thus the continuity equation is given by

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0, \tag{1}$$

and the momentum equation can be written as

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}[\mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k})] + g_i(\rho - \rho_0) - \frac{\partial}{\partial x_i}(\rho\overline{u'_i u'_j}), \tag{2}$$

where Einstein notation is used. In Eq.(2), $\rho\overline{u'_i u'_j}$ is the Reynolds stress tensor that appears as result of the averaging procedure, which has to be modeled to close the system of governing equations, g is the gravity acceleration and δ_{ij} is the Kronecker delta. Finally, the energy equation can be expressed as follows:

$$\frac{\partial}{\partial x_i}(\rho u_i C_p T) = \frac{\partial}{\partial x_i}(\lambda\frac{\partial T}{\partial x_i}) \tag{3}$$

Density is assumed to be constant in Eq.(2), that is, $\rho = \rho_0$, if an imposed inlet velocity is used as boundary condition to analyze the performance of the delta wing. However, when studying the radiator panel the air flows because of buoyancy forces. Therefore, a Boussinesq model is used to take into account the driving force due to a temperature-dependent density. Consequently, the density variation is approximated in Eq.(2) as

$$(\rho - \rho_0)g_i \approx -\rho_0\beta\Delta T g_i, \tag{4}$$

where β is the thermal expansion coefficient of the air ($\beta = 0.0033$ $[1/K]$) and ΔT is the temperature difference which drives the buoyancy force. In this work, the maximum temperature difference between the heated wall and the ambient is $(T_w - T_0) \approx 35$ [K], which is a typical value for electric transformer radiators. Other non-dimensional numbers important for the analysis are the Grashof (Gr), Prandtl (Pr) and Rayleigh (Ra),

$$Gr = \frac{g\beta\Delta T L^3}{\nu^2},\ Pr = \frac{\nu}{\alpha} = \frac{\mu C_p}{\lambda},\ Ra = \frac{g\beta\Delta T L^3\rho}{\mu\alpha} = Gr \cdot Pr, \tag{5}$$

where the kinematic viscosity is $\nu = \mu/\rho_0 = 1.59 \cdot 10^{-5}$ $[m^2/s]$, thermal conductivity is $\lambda = 0.0262$ [W/mK], specific heat is $C_p = 1007$ [J/kgK] and thermal diffusivity is $\alpha = \lambda/\rho C_p = 2.22 \cdot 10^{-5}[m^2/s]$. The characteristic length of the panel is $L_p = 1.524$ [m]. With these physical properties defined, the following values are computed for the non-dimensional numbers: $Gr = 2.74 \cdot 10^5$, $Pr = 0.71$ and $Ra = 1.94 \cdot 10^5$.

Eqs.(1), (2) and (3) are discretized in space using a co-located finite volume method (FVM) [8] implemented in the open source computational fluid dynamic (CFD) code *Code_Saturne* [9]. A 3D segregated solver is used with a SIMPLEC (semi-implicit method for pressure-linked equations consistent) algorithm for coupling between velocity and pressure [10]. A second-order linear upwind (SOLU) method [11] is considered for the convective flux. For turbulence modeling, shear-stress transport (SST) $\kappa - \omega$ is used, where two additional equations have to be solved, one for the turbulent kinetic energy κ and one for the specific dissipation ω. This turbulence model has been used by Oneissi et al. [4], showing good agreement with similar flows. The numerical simulations allow the analysis of global and local quantities in order to evaluate the vortex generator performance, as described in [4].

The local heat transfer coefficient h_l, is defined as follows:

$$h_l = -\frac{q_w}{\Delta T} = -\frac{\lambda\frac{\partial T}{\partial n}}{(T_w - T_b|_x)}, \tag{6}$$

and the local Nusselt (Nu) number is

$$Nu = \frac{D_h h_l}{\lambda} = \frac{D_h q_w}{\lambda(T_w - T_b|_x)}, \tag{7}$$

with q_w being the thermal flux and A the cross-sectional area of the channel.

Finally, an average or global heat exchange coefficient h_g is obtained for the panel surface,

$$h_g = \frac{1}{A_p}\int_{A_p} h_l dA_p, \tag{8}$$

and the average $\overline{Nu}$ number is computed as follows:

$$\overline{Nu} = \frac{D_h h_g}{\lambda} \tag{9}$$

In those problems where the flow is driven by buoyancy forces, the introduction of the VG produces a pressure loss, which decreases the flow velocity. This can reduce the heat transfer coefficient; hence, it is important to evaluate the pressure loss $\Delta \mathrm{P}$ and friction factor f,

$$f = \frac{\Delta \mathrm{P} \mathrm{D_h}}{(\rho \mathrm{L} \bar{\mathrm{u}}^2)/2} \tag{10}$$

Using the Nu number and the friction factor, the TEF can be computed as

$$\mathrm{TEF} = \frac{\overline{\mathrm{Nu}}}{\overline{\mathrm{Nu}}_0} \left(\frac{\mathrm{f}}{\mathrm{f_0}} \right)^{-1/3}, \tag{11}$$

where $\overline{\mathrm{Nu}}_0$ and f_0 represent the average Nu number and the friction factor for the case without the VG, which is taken as reference.

3 Results

3.1 Delta-wing vortex generator performance analysis

The performance of a delta-wing VG is analyzed in this section for different AoA=$\{30;40;50\}$ [deg], inlet air velocities $\mathrm{u_{in}}$=$\{0,3;0.45;0.6;0.75;0.9;1.05\}$ [m/s] and separation distances from the heated wall d=$\{0;3;5\}$ [mm]. The objective of this section is to determine the best configuration in terms of the TEF to achieve a balance between thermal enhancement and pressure loss.

The results of this parametric analysis are shown in Fig.(2). In terms of the TEF, the best performance occurs for AoA=30 [deg] and d=3 [mm], as shown in Fig.(2). Using this configuration the total heat flux increases from 6$\%$ for the lowest velocity to 22$\%$ for the highest one with respect to the reference values ($\mathrm{q_0}$) obtained from the simulation of the flow between parallel plates without the VG.

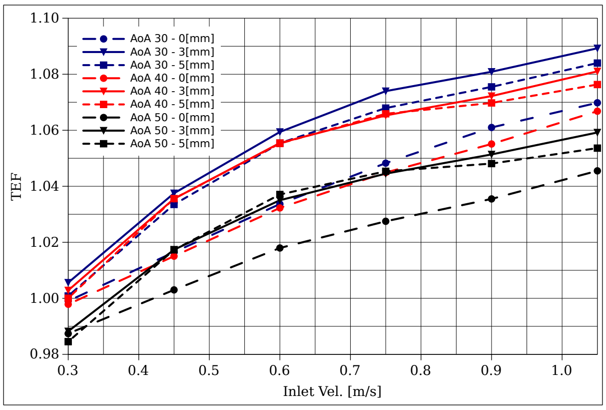

Figure 2. TEF vs. air inlet velocity.

In Fig.(3), the Nu is shown for a flat plate without (left) and with (center) a VG. A centerline ruler with a graduation of one chord ($\mathrm{c} = 12.7$ mm) is placed in the central figure. In the zone between 1c and 3c behind the VG, Nu increases significantly due to the intense inflow toward the panel surface. Downstream of this region the vortices reach a stable position, their intensities decay, and the thermal boundary layer thickness increases. In the outflow region the Nu is reduced in comparison with the reference flat plate values ($\mathrm{Nu_0}$), reaching half the magnitude in some places, which is apparent in Fig.(3) (right). Outside of the inflow / outflow region, $\mathrm{Nu}/\mathrm{Nu_0} \approx 1$.

The downstream evolution of the vortices can be observed in Fig.(4), where the temperature and velocity fields are shown. Several slices along the channel length are shown to visualize the vortices. To easily find the vortex center, the secondary flow is visualized using Line Integral Convolution (LIC) implemented in ParaView. The thermal and fluid boundary layers are reduced in the central (inflow) region, and the thickness increases downstream.

The separation d of the delta wing from the heated wall has a positive effect increasing the heat transfer in the region very close to the delta wing, thus avoiding strong recirculation behind it.

Having determined the optimal configuration of the delta wing by means of a parametric analysis, the next step is to use a delta wing array in a panel type radiator to compute the thermal enhancement for a buoyancy-driven flow.

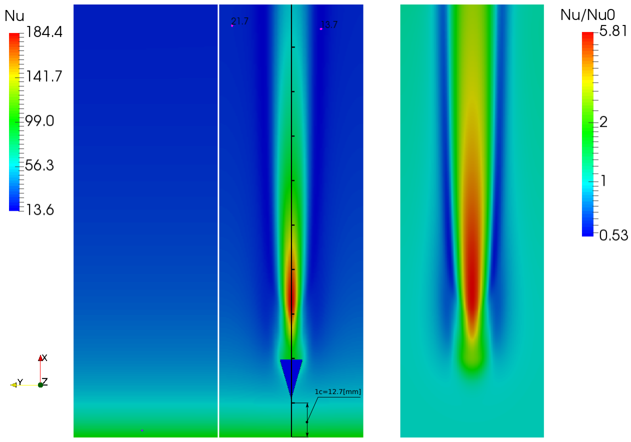

Figure 3. Nu computed without (left) and with a VG (center). Relative $(\mathrm{Nu}/\mathrm{Nu}_0)$ (right).

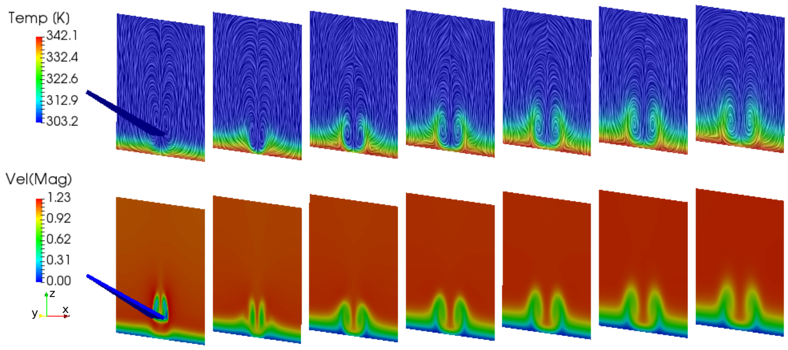

Figure 4. Temperature and velocity fields.

3.2 Panel type radiator with delta-wing arrays

A set of VG arrays are attached to a radiator panel to determine if they enhance the thermal exchange. The flow is driven by buoyancy, unlike the previous case where the air velocity was imposed at the inlet boundary. The total length of the panel is $\mathrm{L_p} = 1524$ [mm], the width is $\mathrm{W_p} = 450$ [mm] and the spacing between panels is $\mathrm{H_p} = 45$ [mm]. The panel has six trapezoidal oil channels, each one of width $\mathrm{W_c} = 75$ [mm] and height $\mathrm{H_c} = 4.5$ [mm]. Three delta wings are placed widthwise on the outer surface of each channel, with 18 VGs used in each array. The arrays are separated by $\mathrm{L_a} = 10 \cdot \mathrm{c} = 127$ [mm], lengthwise with respect to the panel. This distance was selected based on the results of the previous section, where it was observed that the vortex influence on the surface of the panel is $\approx 8\mathrm{c}$. In Fig.(5), the computational domain is shown (drawing not to scale). In this figure, the characteristic dimensions and boundary conditions are denoted. To reduce the computational cost of the simulation, only a quarter of the total domain is simulated using two symmetrical planes (Sym Z and Sym X), at the top of the domain a pressure outlet boundary conditions is set. At the bottom and right side a free inlet / outlet condition is set in order to allow the air flow to enter and exit from the computational domain. Ten delta-wing arrays are placed along the panel, with AoA=30 [deg] and d=3 [mm].

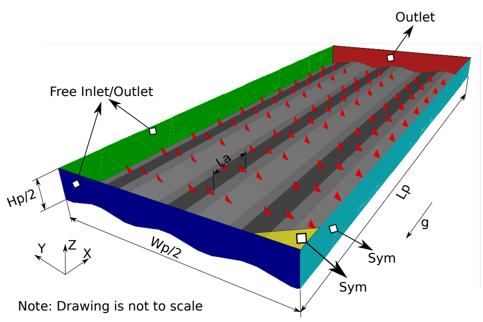

Figure 5. Computational domain with delta wings.

The air inlet temperature is set to $\mathrm{T_{in}} = 303$ [K]. On the other hand, a temperature distribution is imposed on the surface of the heated wall. This distribution is obtained from a conjugate heat transfer analysis for a radiator panel solved by Ríos in [6] and experimentally validated. To simplify the setting of the temperature distribution, an analytic function $\mathrm{T_w = T(x, y)}$ is proposed. This function is linear along the x-axis (longitudinal) and quadratic along the transverse direction (y-axis).

$$\begin{aligned} \mathrm{T_x} &= -10.74 \cdot \mathrm{x} + 338.6, && -0.127 \leq \mathrm{x} \leq 1.397 \ [\mathrm{m}], \\ \mathrm{T_w} &= -147.5 \cdot \mathrm{y}^2 + \mathrm{T_x}, && -0.225 \leq \mathrm{y} \leq 0 \ [\mathrm{m}], \end{aligned} \tag{12}$$

where $\mathrm{T_{w_{max}}} = 340$ [K] (air outlet region) and $\mathrm{T_{w_{min}}} = 323.6$ [K] (air inlet region).

To establish if the heat exchange is enhanced, local and global characteristics are reported. In Fig.(6), the imposed temperature distribution (a) and the heat exchange coefficient (b) are shown. For the panel without VGs, the air enters the region between the radiator fins from the bottom of the panel and from the sides at the given reference temperature; thus, the highest heat exchange coefficient is obtained near the inlet. At a point downstream, the air temperature increases, and the heat transfer coefficient decreases gradually. A similar effect is observed when VGs are used, but now the delta-wing arrays promote the air mixing, locally increasing the heat exchange. VGs placed near the centerline of the panel result in a larger increase than VGs placed near the sides. This is due to a local higher velocity produced by the buoyancy and the chimney effect. Additionally, this effect causes the air entering through the sides resulting in a side-slip angle for delta wings placed near the boundary. From Fig.(6)(c), the positive effect of VGs on the heat exchange coefficient is observed. Without VGs, the corresponding average value is $\mathrm{h_g} = 4.66$ [W/m^{2}K], and with VGs it is $\mathrm{h_g} = 5.4$ [W/m^{2}K]. Therefore, 16% increase is reported.

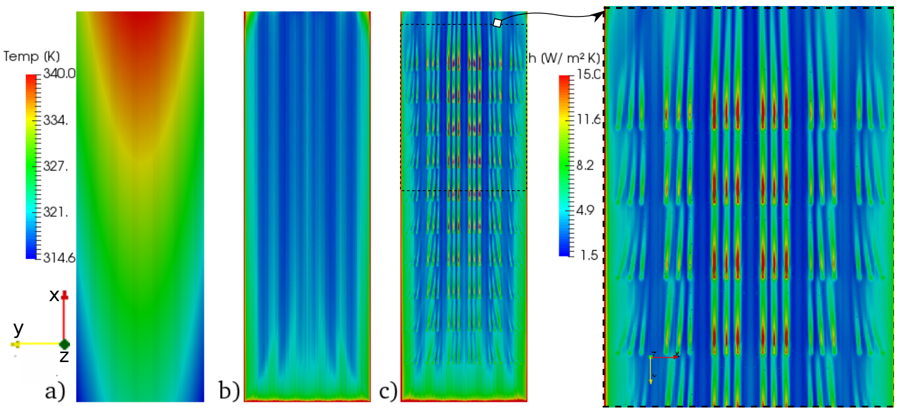

Figure 6. a) Temperature distribution, b) heat exchange coeff. of panel, and c) heat exchange coeff. of panel with VGs.

In Table 1, a summary of global results calculated from both simulations is given. The average outlet air temperature ($\overline{\mathrm{T_{out}}}$), outlet air velocity ($\overline{\mathrm{u_{out}}}$), heat transfer coefficient ($\mathrm{h_g}$) and total heat flux ($\mathrm{q_w}$) are reported. The heat flux increases by 12% when VGs are used.

Table 1. Global result comparison between simulations.

–	$\mathrm{T_{in}}$ [K]	$\overline{\mathrm{T_{out}}}$ [K]	$\overline{\mathrm{u_{out}}}$ [ms^{-1}]	$\mathrm{h_g}$ [Wm^{-2}K]	$\mathrm{q_w}$ [W]	$\mathrm{q_w/q_{ref}}$
Without VGs	303	314	0.48	4.66	32.6	1
With VGs	303	316	0.42	5.41	36.4	1.12

4 Conclusions

In this article, three-dimensional numerical simulations are carried out with the objective of analyzing the performance of delta-wing vortex generators in enhancing the heat exchange coefficient in panel type radiators. The study is focused on natural convection and buoyancy-driven flows, which are the working conditions for this type of heat exchangers.

A parametric study was carried out for three variables, namely, AoA, $\mathrm{u_{in}}$ and d, to determine a configuration that results in the best TEF. The best performance was obtained with $AoA = 30$ [deg] and $\mathrm{d} = 3$ [mm], with an increase in heat transfer ranging from 6% to 22%, depending on the inlet velocity, and a maximum TEF≈10%. Other authors report higher values in heat transfer coefficient enhancement (e.g., Oneissi et al. [4], based on the research of Tiggelbeck et al. [2], reported a maximum $\mathrm{Nu/Nu_0} \approx 1.56$ for $\mathrm{Re} = 4600$), but is important to mention that these values depend on the ratio between the area influenced by the vortex generator and a reference area. In these references, the ratio between the vortex generator span b and the channel width W is $\mathrm{b/W} = 2/5$, where ≈40% of the heated surface is influenced by the vortex generator. In this work, the span $\mathrm{b} = 6.35$ [mm] and $\mathrm{W} = 40$ [mm]; hence, the ratio of $\mathrm{b/W} = 0.158$, and ≈16% is influenced by the vortex generator. If the channel width is reduced to $\mathrm{W} = 15.8$ [mm], then 40% of the heated surface is influenced, with $\mathrm{Nu/Nu_0} \approx 1.6$ for $\mathrm{Re} \approx 5300$, which is in agreement with the results presented by Oneissi et al. [4] and Tiggelbeck et al. [2].

When delta-wing vortex generators are placed in an array configuration on a plate-type radiator and the fluid is driven by buoyancy forces, the pressure loss increases, and the average outlet velocity decreases. However, heat transfer is improved, and the average heat transfer coefficient increases ≈15%, as shown in Table 1. As observed in Fig.(6), VGs placed in the center of the panel produce higher local exchange coefficients ($\mathrm{h_l}$) due to higher local air velocity. In the case of delta wings placed near the lateral side of the air channel, the lower air velocity and side-slip velocity produced by air entering through the sides reduce the efficiency of the device. Anyway, under this condition a 12% increase in heat transfer is obtained, which is a significant improvement.

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