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Numerical study of the influence of the micro pin fin arrangement on the thermal and hydraulic performance of a micro heat sink

Estudio numérico de la influencia del arreglo de las micro aletas en el desempeño térmico e hidráulico de un micro disipador de calor

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Abstract

In this project, a numerical study of the thermal and hydraulic performance in a micro pin fin heat sink is carried out. The micro heat sinks pin fins are used for cooling of electronic, due that every day a more powerful and smaller chips and electronic components are required. The geometric parameters to the build of the heat sink with micro pin fins are chosen in base of the geometric needs of the electronic chip, a circular geometry is used for the micro pin fin and inline and staggered arrangement for the micro pin fins distribution is used, different velocities in the inlet of the heat sink are used for development of the study. In the result section, the temperature contours and the thermal resistance of the different cases analyzed are reported, as well as the pressures distributions and the total pressure drop along the heat sink micro pin fin are reported too. Taken account the results, the optimal geometry for thermal and hydraulic performance of the heat sink micro pin fin is obtained.

Heat sinks, Micro pin fins, Thermal resistance, Pressure drop

Resumen

En el presente proyecto se realiza un estudio numérico del desempeño térmico e hidráulico de un micro disipador de calor con micro aletas. Estos disipadores son usados en el enfriamiento de chips electrónicos, ya que día con día se tienen chips más potentes y pequeños. En base a las necesidades geométricas del chip electrónico se eligen los parámetros geométricos para la construcción de la geometría del disipador de calor con micro aletas, se utiliza la geometría circular para las micro aletas, se usa el arreglo en línea y el escalonado para la distribución de estas. Se utiliza agua como fluido de enfriamiento, se hace el análisis para diferentes velocidades de entrada del fluido. Dentro de los resultados reportados están los contornos de temperatura y la resistencia térmica de los diferentes arreglos de las micro aletas, así como también la distribución de presión y la caída de presión total a lo largo del disipador, esto para diferentes números de Reynolds. Tomando en cuenta los resultados se elige la geometría óptima para el mejor desempeño térmico e hidráulico del disipador de calor con micro aletas.

Disipadores de calor, Microaletas, Resistencia térmica, Caída de presión

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Introduction

Over the years there have been important technological contributions in the area of electronic devices, which has required electronic circuits with increasingly better performance and greater energy efficiency, as well as the reduction of noise during operation; In addition to this, their size has also been required to be smaller and smaller, reaching measurements of micrometres and sometimes even nanometres, to meet the needs of the consumer, as more powerful and faster systems are required, but also smaller and lighter, which is more comfortable for the user, especially in portable devices such as mobile phones, computers, tablets, etc.

The use of very small electronic chips has brought an important problem to solve, which is the generation of hot spots in these devices, these spots are generated because the designs are complex and the power distribution within the chips is often not adequate, resulting in the generation of these hot spots, which produce high temperatures, which in turn reduce the performance and life of the chips and in most cases irreparable damage to them.

To solve these heating problems, it is of utmost importance to incorporate cooling systems to electronic chips, but due to their design and the amount of heat generated inside them, conventional cooling techniques based on forced convection through air are not enough, due to the size of the microprocessor, so new cooling techniques must be used, one of these techniques is liquid cooling through microchannels.

In the early 2000s, (S. G. Kandlikar, 2005) proposed different scenarios in which the technique of liquid cooling by means of microchannels is applied to electronic devices, resulting in this being the best cooling technique, especially when working with heat flows greater than 100 W/cm^2.

This technique has been improved over the years, micro fins have been implemented in many occasions instead of microchannels, which have been studied with different geometric configurations, offering improvements in heat transfer increases according to the geometry of the micro fin used; Similarly, different types of microfin arrangements have been tested, such as in-line and staggered arrangements, and different types of cooling fluids have been used, with nanofluids being one of the best options to increase heat removal.

Background

The first record of the use of liquid cooling by means of microchannels is reported by (Tuckerman & Pease, 1981), who implemented microchannels in a heat sink and used water as a cooling fluid, they managed to dissipate a heat flow of up to 790 W/cm^2, which acted constantly on the surface of the heat sink.

In their work (S. Kandlikar et al., 2005), they publish on fluid mechanics and heat transfer in mini-channels and microchannels analysed under a single phase, they provide the theoretical basis for this type of analysis, as well as some correlations for the calculation of the pressure drop and the convective coefficient of heat transfer. In another paper (S. G. Kandlikar, 2005), he describes how by using microchannels it is possible to dissipate heat fluxes of up to 1 kW/m^2.

Since then, the use of microchannels has increased considerably, especially in applications where a large amount of heat flow must be removed and the space to install heat sinks is very small. To improve this technique, the use of mini and micro fins has been employed to increase heat transfer, with good results in terms of thermal performance so far.

Numerical analyses have been developed to investigate the performance of micro finned heat sinks, different micro fin geometries and different type of cooling fluid have been analysed, for example, (Saravanan & Umesh, 2018), compared the fluid flow and heat transfer characteristics for a micro finned heat sink and the microchannel heat sink without fins. They used a constant heat flux of 10 W/cm^2, for Reynolds numbers between 100 and 900. Square and circular micro fins, with an in-line and staggered arrangement, are considered.

The results indicate that the finned heat sink has a higher Nusselt number and friction factor. The micro-fin geometry that offers the best heat transfer is the square fin. Also, the finned heat sink has a better thermal performance index compared to the microchannel-only heat sink and is more preferable when heat dissipation is compared to the pressure drop penalty.

On the other hand, (Karami et al., 2019), perform a numerical simulation of a heat sink with micro fins and placing a baffle for a water flow for a range of $50 \leq Re \leq 250$. They investigate the type of baffle and its dimensions, with this they find out the effects of it on the overall performance of the heat sink. The baffles they used are single, double and triple segment baffles, with four different overlaps, classified as 60%, 40%, 20% and 0%. Their results compare them with a micro-fin heat sink without baffles. In their results they show that the use of fin baffles increases the heat transfer, but also increases the pressure drop. The heatsink with a 20% overlapping double segment baffle has the highest heat transfer.

(Alam et al., 2020), perform a numerical analysis to investigate the behaviour of a triangular micro-finned heat sink used in a central processing unit (CPU), they report the heat transfer and pressure coefficient for different Reynolds numbers. In their work they consider the effects of turbulence intensity in the system. Similarly, (He et al., 2021), propose a heat sink with ribbed micro fins, which they compare with a smooth microchannel and circular micro fins with an in-line arrangement. In their results they report an increase in the Nusselt number when using the ribbed fins, resulting in almost a two-fold increase compared to circular microfins with an in-line arrangement and three times more compared to a smooth microchannel. This results in better thermal performance.

(Gupta et al., 2021), study the hydrodynamic and thermal characteristics of a heat sink with perforated micro fins, the micro fins are of different shape and the number of perforations also vary. The results they report show that heat sinks with perforated micro fins provide higher Nusselt number values and lower pressure drop levels than with non-perforated micro fins. These perforations have also shown a higher efficiency of the micro fins compared to non-perforated micro fins. In addition, when perforations are used, the performance is superior to non-perforated ones. The shape of the perforation is also analysed, resulting in a circular shaped perforation being more efficient, followed by elliptical and square perforation.

Experimental analysis includes work by (Kewalramani et al., 2019), who analysed the hydrothermal characteristics of a micro heatsink with elliptical micro fins with a constant heat flux over the base of the heatsink. They performed experiments on the heatsinks using deionised water as the cooling fluid. They developed a numerical model for a single-phase incompressible laminar flow and validated it with experimental results. In their results they find that the behaviour of the local heat transfer coefficient. They propose a length scale selection criterion to define the Reynolds number, the Nusselt number and the friction factor and develop correlations describing the behaviour of the Poiseuille number and the Nusselt number with respect to the Reynolds number and the Prandtl number. These correlations can be useful in the design of elliptical micro-fin heat sinks.

In the area of micro finned heat sink optimisation, models have been developed to predict the pressure drop behaviour, (Lee et al., 2021), develop an artificial neural network to predict the thermal and hydrodynamic performance of finned micro heat sinks used in high heat flux electronic devices. They use a wide variety of geometric, operating and hydraulic performance conditions to train the artificial neural network as accurately as possible. Their results are compared with correlations based on the regression method, obtaining superior performance with their model. Other optimisation studies are developed by (Chen et al., 2017), who carry out the optimisation of finned micro heat sinks using contract theory and minimum entropy generation.

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With this optimisation technique, the influence of material, heat transfer and fluid velocity will be taken into account, which represents a more complete analysis. In their results they report the optimal diameters for the fins. For the formulation of their objective function they take into account the geometrical parameters and the number of fins, determining the influence of material, heat transfer and fluid velocity on the results.

In this work a micro heat sink with micro fins is analysed, which have a circular geometry, in line and staggered arrangements are considered for the micro fins, a configuration for the staggered arrangement is proposed, which consists of the micro fins that are deflated having a different diameter to the non deflated fins, this with the aim of not affecting the pressure drop to a large extent. The cooling fluid used is water at 293 K. The material of which the heat sink is made is silicon and a constant heat flow is applied to the base of the heat sink.

Geometry

For the analysis of the micro heat sink with micro fins, we start from the construction of the geometry to be studied, for this construction we make use of the symmetry tool, that is, we will take only one area of interest, which represents what happens in the complete domain to be analysed, with this we will save time and computational resources.

Figure 1 shows the segment of the heat sink with micro fins being analysed, the geometry of the micro fins used is circular, the dimensions of the micro fins and the heat sink are shown in the figure. It can be seen how the symmetry condition is taken, in order to simplify the computational model. The arrangement depicted in Figure 1 is the in-line arrangement for the micro fins.

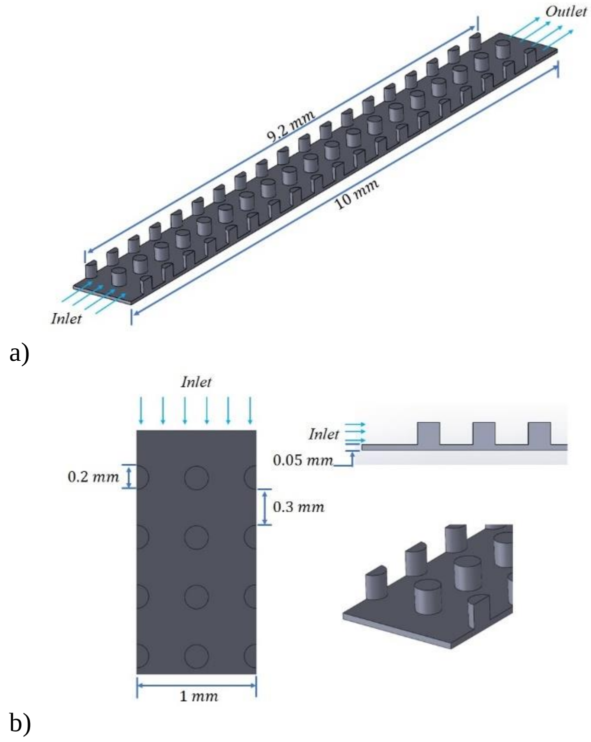

Figure 1 Geometry of the heat sink with micro fins considered for numerical analysis. a) Heatsink and b) top, side and isometric views
Source: Own elaboration.

Figure 2 shows two of the arrangements analysed for the placement of the micro fins, a) shows the in-line arrangement, which is the arrangement commonly used for forced convection heat sinks using air. (b) shows a staggered arrangement, which causes a row of micro fins to be placed in the middle of the flow line, forcing the flow to have directional changes along its flow line. S_T represents the transverse spacing between the micro fins and S_L the longitudinal spacing, which for the analysis cases are both 0.5 mm.

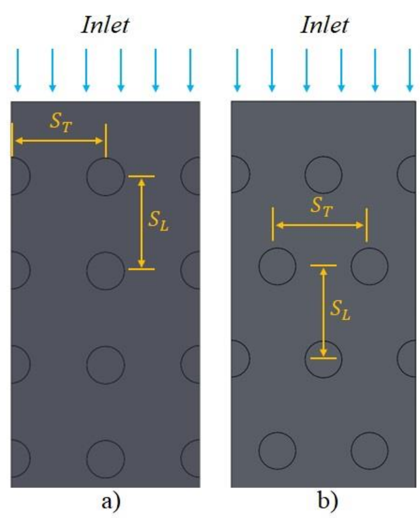

Figure 2 Arrangement of the micro fins on the heat sink. a) in-line arrangement and b) staggered arrangement
Source: Own elaboration

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Figure 3 shows the arrangement of the micro fins proposed in this research, which is based on the arrangement proposed by (Bello-Ochende & Bejan, 2005), who used this arrangement to increase natural convection heat transfer by using cylinders of various sizes and optimally placed. In a cylinder arrangement, they place smaller cylinders at the entrance of the assembly, so that the smaller cylinders occupy the space that is not used for heat transfer. Although this arrangement is used in natural convection, it is being studied to investigate its performance under forced convection in micro-finned micro heat sinks.

For this arrangement we have to combine different diameters of the microfins, following the ratio Ø_o⁄Ø_1, thus the first row of fins corresponds to the diameter Ø_o (larger diameter) and the second row to the diameter Ø_1 (smaller diameter), as can be seen in Figure 3 b). The transverse and longitudinal spacing is the same as for the staggered arrangement.

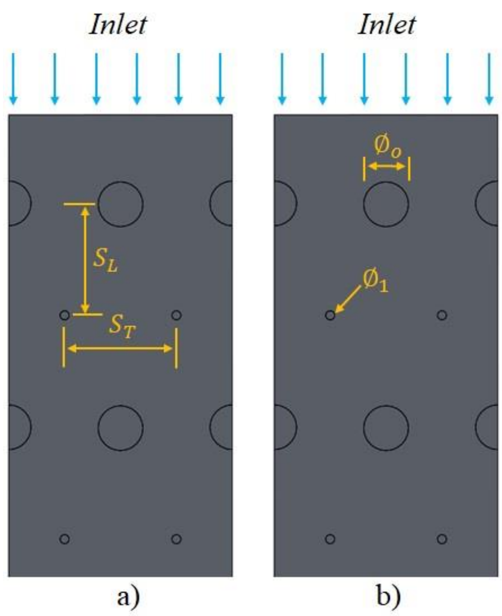

Figure 3 Arrangement of the micro fins on the heat sink
Source: Own elaboration

Case	Arrangement	$\emptyset_o/\emptyset_1$
1	In line	Not applicable
2	Staggered	1
3	Staggered	0.8
4	Staggered	0.6
5	Staggered	0.4
6	Staggered	0.2

Table 1 Cases of the different geometrical models analysed for the different arrangements
Source: Own elaboration

Table 1 shows the different cases analysed in this study, in Case 1 an in-line array is analysed, in cases 2 to 5, geometric staggered arrays are analysed, in which the diameter of the second row is varied as in Figure 3, the ratio of Ø_or⁄Ø_1, from 1 to 0.2, is used.

Computational analysis

A mesh is constructed for the numerical analysis, one of the constructed meshes is shown in Figure 4. It can be observed how the mesh adapts perfectly to the geometry, thus avoiding the generation of negative volumes or areas with a non-uniform mesh.

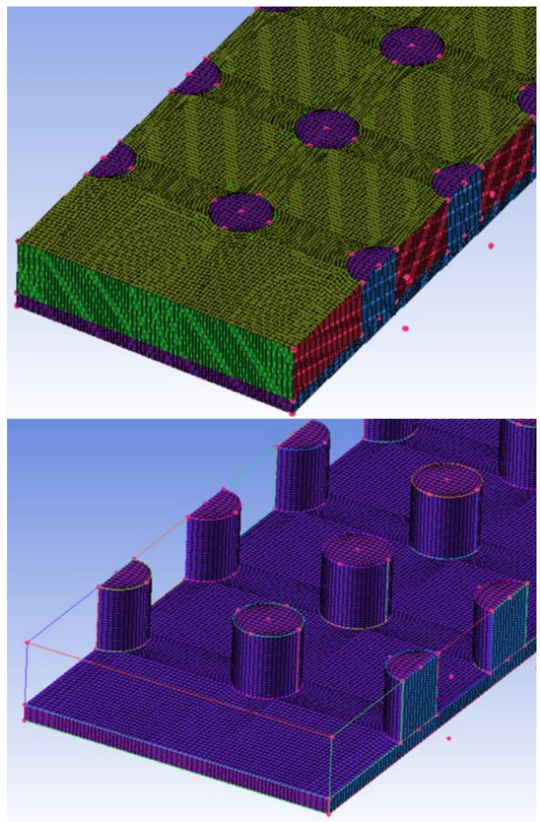

Figure 4 Mesh constructed for numerical analysis
Source: Own elaboration

Graphic 1 shows the mesh sensitivity analysis carried out, it can be seen how the temperature varies with the increase in the number of nodes, until it stabilises and no longer produces any change, with this we can take that the mesh with a number of elements of 1,545,600 is the one that can be taken to carry out the numerical analysis.

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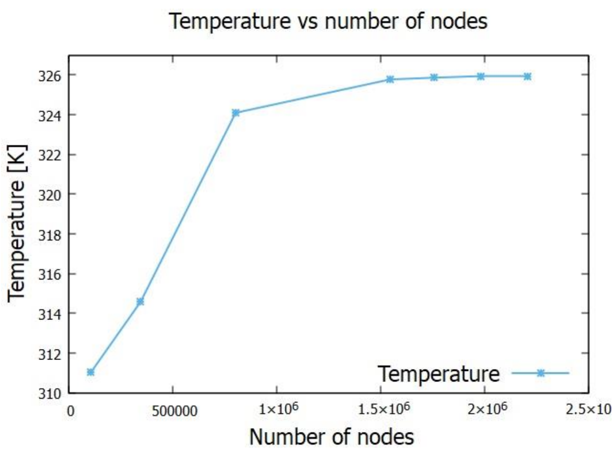


Graphic 1 Change of the temperature at the heatsink base for different numbers of nodes
Source: Own elaboration

Figure 5 shows the boundary conditions used for the numerical simulation, an inlet velocity, an outlet pressure, at the base of the heat sink, the application of a constant heat flow is considered, which is 60,000 W⁄m^2 and the symmetry condition is used on both sides of the geometry, thus reducing the computation time to obtain the results.

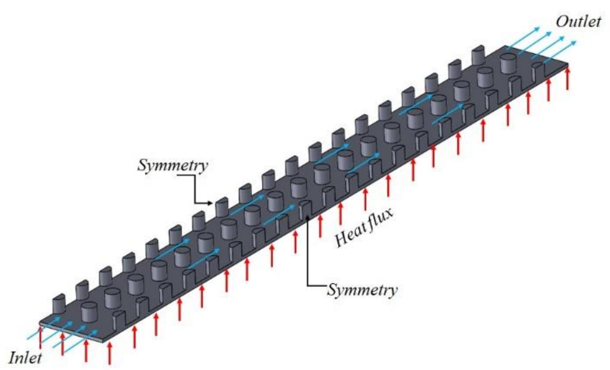


Figure 5 Boundary conditions taken to perform the numerical simulation
Source: Own elaboration

Once the boundary conditions are considered, the following considerations are taken into account:

- Steady state for heat transfer.
- Incompressible flow.
- Constant thermophysical properties.
- Flow in a laminar regime.
- A water fluid inlet temperature of 293 K.
- The heat flux considered at the base of the heatsink is 60,000 W⁄m^2.

The material considered for the numerical analysis of the heat sink with microfins is silicon, because a large number of electronic components are manufactured with this material, and water is used as the working fluid for cooling the heatsink. The thermophysical properties of silicon and water considered for the numerical analysis are presented in Table 2.

Property	Value
Water	
Thermal conductivity (W/mK)	0.5948
Specific heat (kJ/kgK)	4.183
Density (kg/m^3)	997.1
Viscosity (kg/ms)	0.0008905
Silicon	
Thermal conductivity (W/mK)	148
Specific heat (kJ/kgK)	0.712
Density (kg/m^3)	2330

Table 2 Thermophysical properties of the working fluid and the silicon
Source: Own elaboration

The equations governing the analysed phenomenon are: for the fluid, the energy equation (Equation 1), conservation of mass (Equation 2) and the momentum equation (Equation 3).

$$\rho_f C_{pf}(\vec{V} \cdot \nabla T) = k_f \nabla^2 T \quad (1)$$

$$\nabla \cdot \vec{V} = 0 \quad (2)$$

$$\rho_f(\vec{V} \cdot \nabla \vec{V}) = -\nabla P + \mu \nabla^2 \vec{V} \quad (3)$$

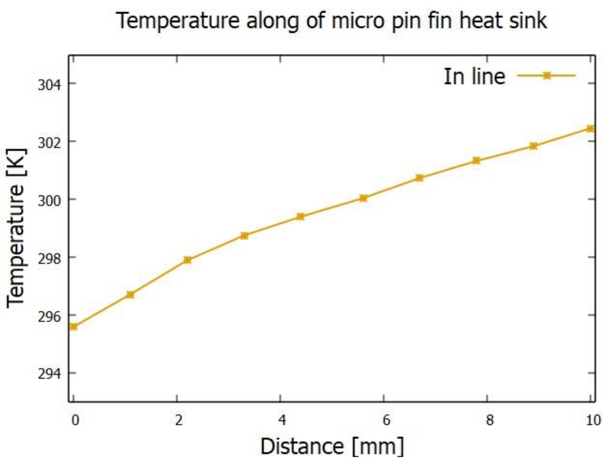
For the micro finned heat sink, only the energy equation (Equation 4) is considered:

$$\nabla^2 T = 0 \quad (4)$$

Results

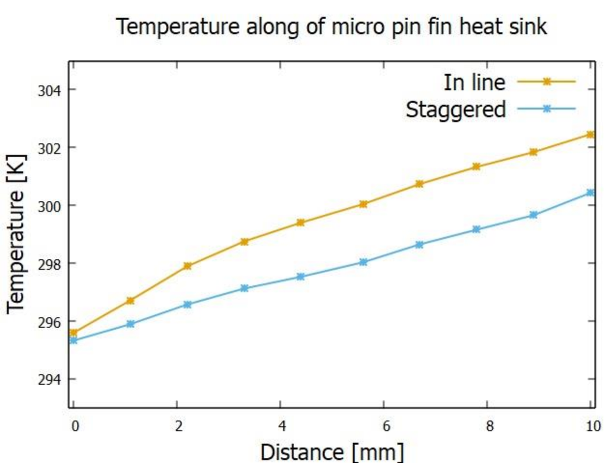
This section shows the thermal and hydrodynamic results of the numerically studied cases, the temperature profiles at the base of the micro-finned heat sink, the temperature and pressure distribution contours along the heat sink, as well as the thermal resistance and the total pressure drop along the micro-finned heat sink.

Graphic 2 shows the behavior of the temperature profile along the heatsink base when using an in-line micro fin array (Case 1), the effect of the cooling fluid on heat removal at the base of the heatsink, the lowest temperature occurs at the inlet of the heatsink and the highest temperature occurs at the outlet, obtaining an average temperature of 299.56 K over the entire surface of the heatsink.



Graphic 2 Temperature at the base of the heatsink with micro fins for a Re = 100
Source: Own elaboration

To observe the effect of the different arrangements of the micro fins on the cooling of the heat sink, Graph 3 shows the comparison of the in-line arrangement and the staggered arrangement, which correspond to Case 1 and Case 2, respectively. It can be seen that the staggered arrangement has a better thermal performance, since it has an average temperature of 297.62 K over the entire surface of the base of the heat sink, which is lower than that of the in-line arrangement.



Graphic 3 Temperature comparison of a microfin heatsink with an in-line array and a staggered array, for Re = 100
Source: Own elaboration

Figure 6 shows the temperature contours along the base of the heat sink for Case 1 and Case 2, it is clearly observed how the lowest temperatures are obtained in the staggered arrangement, it is also observed that there are no heating points, obtaining a uniform distribution along the entire base.

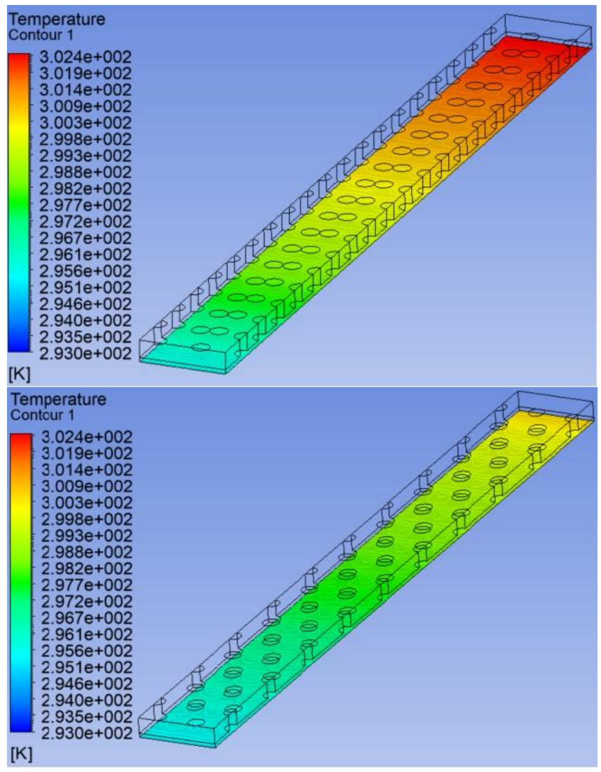


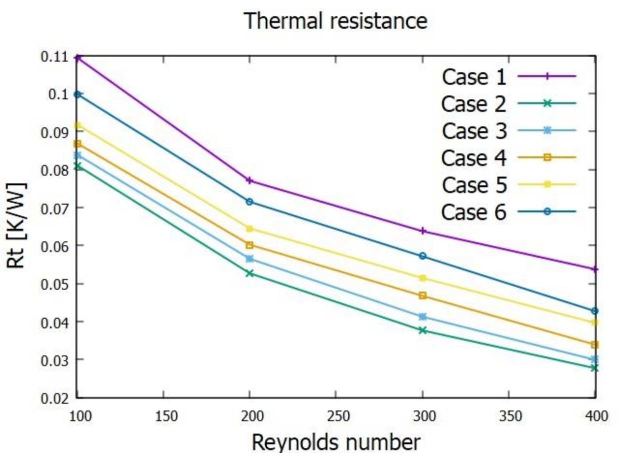
Figure 6 Comparison of the temperature contours of a micro-finned heatsink with an in-line array (Case 1) and a staggered array (Case 2), for Re=100
Source: Own elaboration

One of the parameters that provides information about the thermal performance of the heat sink is the thermal resistance, which indicates how easily heat can be transferred through the heat sink to the fluid and thus removed to the outside. The thermal resistance can be calculated with the following equation:

$$R_t = \frac{T_s - T_{ent,f}}{q''} \quad (5)$$

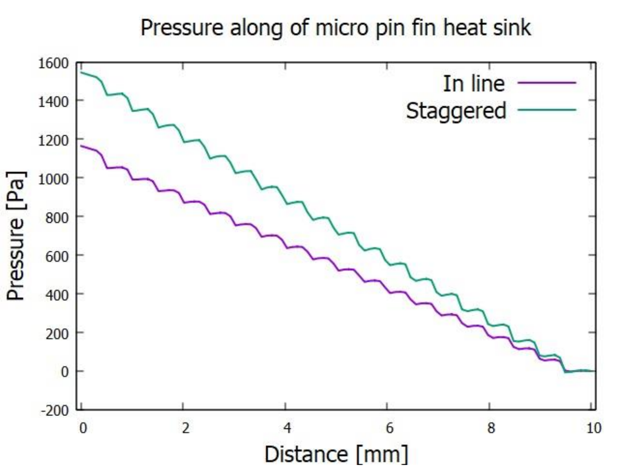
Where the variable T_s is taken as the surface temperature of the heatsink base, T_(ent,f) is the temperature at which the cooling fluid enters the heat sink and q" is the heat flux supplied at the base of the heatsink.

Graphic 4 shows the thermal resistance calculated with Equation 5 for all the cases studied, considering different Reynolds numbers. It can be seen that the case with the highest thermal resistance is Case 1, which corresponds to the in-line arrangement, and the case with the lowest thermal resistance is Case 2, which is the staggered arrangement. For the other cases, it is observed that the larger the diameter of the microfins in the second row, the lower the thermal resistance.



Graphic 4 Comparison of thermal resistance for the different cases analyzed
Source: Own elaboration

Another important parameter to analyse is the pressure necessary to move the cooling fluid inside the heat sink with micro fins. Graph 5 shows the fluid pressure along the heat sink, comparing the in-line arrangement and the stepped arrangement; the results show that the stepped arrangement requires a higher pressure to move the fluid inside the arrangement, but it is also the one with the lowest thermal resistance, as shown in Graphic 4.

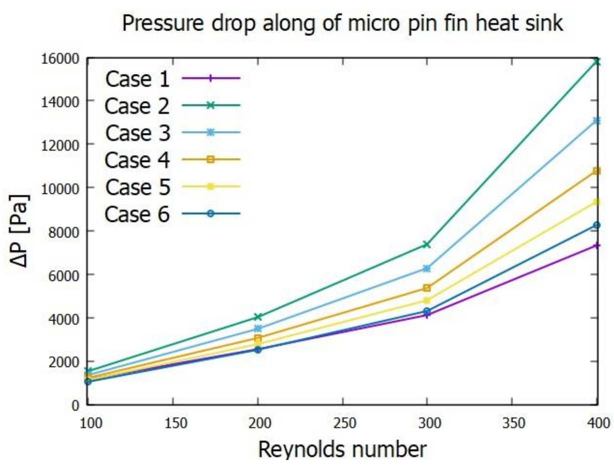


Graphic 5 Comparison of pressure along the micro finned heatsink with an in-line array and a staggered array
Source: Own elaboration

The following equation is used to calculate the pressure drop across the heatsink:

Where P_{ent} is the pressure at the inlet of the micro-finned heat sink and P_sal is the outlet pressure across the heatsink. The results of the pressure drop for the cases studied are reported in Graphic 6.

In Graphic 6, a comparison of the pressure drop across the heat sink is made for the different cases studied for different Reynolds numbers. As expected, the one with the highest pressure drop is the staggered arrangement, the one with the lowest drop is the in-line arrangement, and for the other cases, as the diameter of the second row of fins increases, the pressure also increases.



Graphic 6 Comparison of pressure drop along the heatsink
Source: Own elaboration

From the results of the pressure drop shown in Graphic 6, it can be seen that the pressure drop of Case 1 and Case 6 have very little difference, where Case 1 corresponds to the in-line arrangement and Case 6 to the stepped arrangement when using a ratio of ∅_or⁄(∅_1=) 0.2, this result is relevant because with the same magnitude of pressure drop there are different thermal resistances, being lower in Case 6.

$$\Delta P = P_{ent} - P_{sal} \quad (8)$$

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Conclusions

Numerical analysis of a heat sink with micro fins is carried out, the geometry of the micro fins is circular. The geometry of the heat sink is constructed, considering two types of arrangements for the micro fins, the in-line arrangement and the staggered arrangement, this type of arrangement is the one commonly used in cross-flow heat exchangers used in the petrochemical industry.

For the staggered arrangement it is considered to use a variant, the second row of micro fins will have a smaller diameter than the first row, using the ratio of ∅_or⁄∅_1.

The construction of the mesh is carried out and a mesh sensitivity analysis is performed to obtain the best mesh to be used in the numerical study.

The results show that the heat sink with an in-line micro-fin array maintains an average temperature of 299.56 K over the base of the heatsink, which indicates that it would keep the electronic chip working at allowable temperatures. When using the staggered array for the micro fins this average temperature is even lower, being 297.62 K.

The pressure drop results are reported for each of the cases analysed, from the results it can be concluded that the highest pressure drop occurs when using the stepped array in Case 2, and the lowest pressure drop occurs in the in-line array (Case 1) and in the stepped array with a ratio of ∅_or⁄(∅_1=) 0.2 (Case 6).

From here it can be concluded that the stepped arrangement is the one with the lowest thermal resistance, but it is also the arrangement with the highest pressure drop, so a balance must be found between thermal resistance and pressure drop, taking into account these two parameters it can be concluded that the geometric arrangement with the best thermal and hydraulic performance is the stepped arrangement of Case 6, which is the one with a ratio ∅_o⁄(∅_1=) 0. 2, this will have a lower thermal resistance compared to the in-line un arrangement and a pressure drop of the same magnitude as the in-line un arrangement.

Acknowledgements

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Nomenclature

k	Thermal conductivity, (W/m-K)
c_p	Specific heat, (kJ/kg-K)
q''	Heat flux, (W/m2)
Rt	Thermal resistance, (K/W)
T	Temperature, (K)
ΔP	Pressure drop, (Pa)
S_T	Transverse micro-fin spacing, (mm)
S_L	Longitudinal spacing between micro fins (mm)
$\vec{V}$	Velocity vector
	Greek symbols
$\emptyset_o$	Largest diameter (mm)
$\emptyset_1$	Minor diameter (mm)
ρ	Density, (kg/m3)
μ	Dynamic viscosity, (kg/m-s)
f	Subscript
ent	Fluid
sal	Inlet

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