XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

EFFECT OF MICRO PIN-FIN GEOMETRY ON HEAT TRANSFER PERFORMANCE AND FLUID FLOW IN A SINGLE-PHASE HEAT SINK: NUMERICAL AND EXPERIMENTAL ANALYSIS

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Abstract. The growing demand for electronic devices with high processing capacity with increasingly smaller dimensions has been requesting solutions from the scientific community to dissipate the high rates of heat generated in such devices, ensuring their integrity and functioning. Thus, research on applications in compact heat sinks, such as micro pin-fins, has gained visibility, mainly associated with using environmentally friendly working fluids. In this context, the current work analyzes the thermal and hydrodynamic behavior of HFE-7100 in a heat sink based on different shape pin-fins. Moreover, different micro pin-fins (with 350 µm height) arrays, in-line and staggered configurations, are tested at different mass velocities. Thus, a numerical and experimental study is carried out on the single-phase heat transfer and pressure drop characteristics. The numerical results showed a good agreement with the experimental data for both geometries and operational conditions analyzed, with a mean absolute error lower than 3.1% for heat transfer coefficient and 12.8% for pressure drop. The results showed that the surfaces with staggered arrays present slightly better thermal performance than the in-line arrays, probably due to the highest number of pin-fins. The staggering array yielded a higher Nusselt number at the same mass velocity, which can be explained by the higher flow velocity and enhanced flow mixing. Regarding the hydrodynamic aspects, the numerical data sets for in-line and staggered pin-fin configurations have the same tendency, increasing with the mass flux. However, the in-line pin-fin values are higher, probably due to the diamond pin-fin shape for the staggered configuration, which, compared to the in-line square shape pin-fins, causes a reduced disturbance to the flow, giving smaller pressure drops. To conclude, both the in-line and staggered configurations of the heat sink are reasonable solutions for the current cooling challenge, with an advantage for the staggered configuration compared to the in-line configuration.

Keywords: CFD, heat transfer coefficient, HFE-7100, pin-fin array effect.

1 Introduction

In the face of the need for cooling electronic devices that are applied in multiple areas of industries nowadays, heat sinks geometries have been emerging as a solution that guarantees the security of projects in terms of temperature control, not allowing damages from heat sources to compromise data. This device also occupies minimum space once it can be manufactured by microscale processes, presenting a reduced dimension and allowing components to work at maximum efficiency. It also works under higher pressure operational conditions due to its structural characteristics.

Microscale refrigeration systems can cool high-generation electronic devices and appliances since the heat transfer performance of a microchannel-based heat sink is superior to any traditional heat exchanger [1]. Compact heat sink devices present other advantages compared to traditional ones, such as a superior ratio of fluid contact area per volume of refrigerant, a reduced fluid inventory, costs, environmental impacts, and higher heat transfer coefficient under higher pressure drops. In addition, it is possible varying the refrigerant fluid's properties to increase the system's efficiency [2].

The existence of micro fins or pillars can increase the heat transfer area and introduce disturbances in the flow. Thus, the arrangement, the geometric shape, the height/diameter ratio, and the porosity of the fins have a key influence on the thermal performance and the hydraulic characteristics of the heat sink. According to [3], fluid disturbance positively affects heat transfer but can also increase pressure loss. As validated by [4], a numerical model used to study the effect of different geometric characteristics on the hydrodynamic and thermal characteristics of heat sinks with in-line fins showed that if the shape of the cross-section in contact with the flow is changed, the heat transfer can be optimized. So, besides enabling new technologies related to the miniaturization of equipment and the dissipation of high heat rates, micro pin-fins make possible operational cost reductions and equipment manufacturing, directly impacting the environment.

Methods based on computational fluid dynamics (CFD) are robust tools for simulating fluid flow and thermal behavior, considering that it numerically solves equations regarding fluid flow and heat transfer problems inside a defined geometry. As claimed by [5], CFD presents the crucial and fundamental understanding of the parameters such as velocity, pressure, and temperature field, providing the most valuable designs and better efficiency of microchannel heat sink devices.

Within this context, the present work aims to numerically study using Ansys Fluent® the pressure drop, velocity field, and wall temperature of two different geometries of a micro pin-fin (in-line square and staggered diamond shape pin-fins), both with 350 μm height, in a single-phase flow of HFE-7100 coolant. The numerical results are compared with the experimental ones, which the research group obtained. The motivation lies in applying the developed methods and results to optimize cooling systems applicable to aerospace and electronic fields.

2 Methodology

The methodology consists of defining the input parameters (copper is applied in both cases as the heat sink material). For consistency in the analysis, the results obtained numerically for the single-phase flow regime are compared to those obtained experimentally, considering the same conditions.

The analysis comprises two cases: Case 1 corresponds to the in-line square shape pin-fins, and Case 2 corresponds to the staggered diamond shape pin-fins; both are compared with their equivalent experimental results. Table 1 and Figure 1 show the heat sink configuration cases. Inlet mass flux and dimensions of the micro pin-fins are from the experimental approach. The heat flux is distributed through the micro pin-fins except for the top side (a polycarbonate piece thermally insulated the heat sink); for the inlet and outlet plenums, adiabatic wall conditions are considered.

Table 1. Heat sink geometry parameters.

Geometric parameters	**Case 1**	**Case 2**
Number of pin-fins [-]	972	988
Length of the heat sink [mm]	0.30	0.30
Pin-fin width [mm]	0.30	0.30
Pin-fin height [mm]	0.35	0.35
Inter-fin space [mm]	0.25	0.25

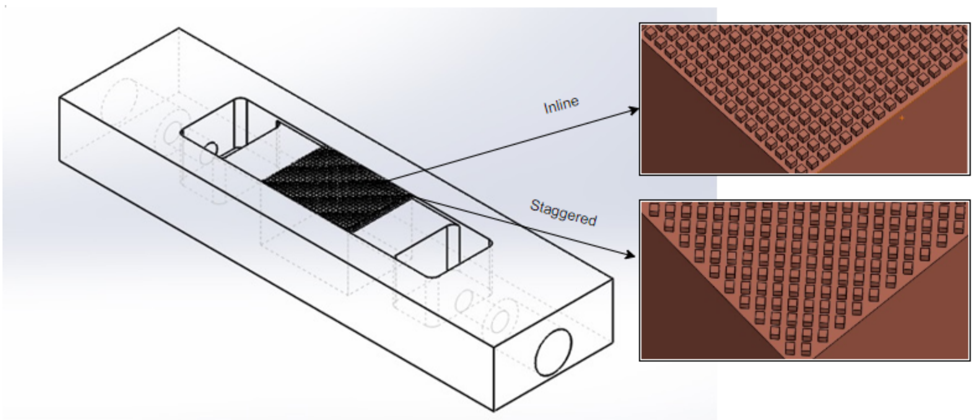

Figure 1. Design of the micro pin-fin heat sink showing the different pin-fin shapes.

The pumping power is correlated with the system's pressure drop and, in turn, with the flow and working fluid (high flow rates and higher viscosities provide increased pressure drop) and the heat sink's geometry. Thus, the thermal model development includes a tridimensional analysis, steady-state, single-phase, laminar flow, variable thermophysical properties with the boundary conditions, and uniform heat flux distribution at the bottom of the heat sink.

The inlet temperature of the working fluid (HFE-7100) was considered 297.6 K (atmospheric pressure of 98 kPa), and the input power was 12 W. The thermal insulation consists of a polytetrafluoroethylene piece (PTFE); the working fluid is not heated before contacting the micro pin-fins since the inlet and outlet plenums are placed in the PTFE piece.

For both Cases 1 and 2, the thermophysical properties of the material and the working fluid are presented in Table 2. The current study's thermophysical properties considered the dependence on input data (inlet boundary conditions).

Table 2. Thermophysical properties of the working fluids and heat sink material.

Thermophysical properties	**Copper**	**PTFE**	**Case 1**	**Case 2**
Density [kg/m^3]	8978	2200	1483.60	1480.46
Specific heat [J/kg K]	381	1000	1181.20	1183.98
Thermal conductivity [W/m K]	387.6	0.25	0.06902	0.06873
Viscosity [kg/m s]	-	-	0.000623	0.000635

2.1 Numerical operational parameters

The fluid flow was assumed steady-state, incompressible, and laminar, which is solved by adopting the Finite-Volume Method implemented in ANSYS Fluent 2020 R2. As a reference pressure, atmospheric pressure is defined; by considering the characteristics of a low-pressure system, the outlet pressure is set up as zero. No-slip condition is considered on the surfaces. Figure 2 presents a scheme of the computational domain with appropriate boundary conditions. Based on these assumptions, the governing differential equations used to describe the fluid flow and heat transfer in the micro pin-fins are given as:

Continuity (mass conservation):

$$\nabla.(\rho \boldsymbol{V}) = 0 \tag{1}$$

Conservation of momentum:

$$\boldsymbol{V}.\nabla(\rho \boldsymbol{V}) = -\nabla p + \nabla.(\mu \nabla \boldsymbol{V}) \tag{2}$$

Fluid (conservation of energy):

$$\boldsymbol{V}.\nabla\left(\rho c_p \boldsymbol{T}\right) = \nabla.(k_l \nabla \boldsymbol{T}) \tag{3}$$

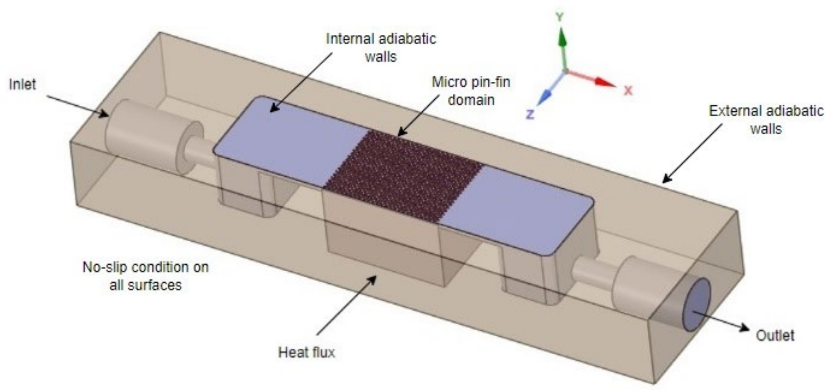

Figure 2. Computational domain of the heat sink with main boundary conditions.

The simulation is based on the mass, momentum, and energy conservation equations with the second-order upwind scheme for energy and pressure and the first-order for the momentum. The fluid flow is assumed as steady-state, incompressible, and laminar. The heat flux is applied at the bottom of the micro pin-fins, and adiabatic wall conditions were considered for the inlet and outlet plenums.

The hex dominant meshing grid scheme with a free face mesh type combining triangles and quadrilaterals is used to mesh the systems (for both cases), as shown in Figure 3. The mesh is accomplished in the meshing module with minimum mesh orthogonality of 0.311 (Case 1) and 0.346 (Case 2), a maximum aspect ratio of 17.42 (Case 1) and 18.65 (Case 2), and a maximum skewness of 0.56 (Case 1) and 0.61 (Case 2).

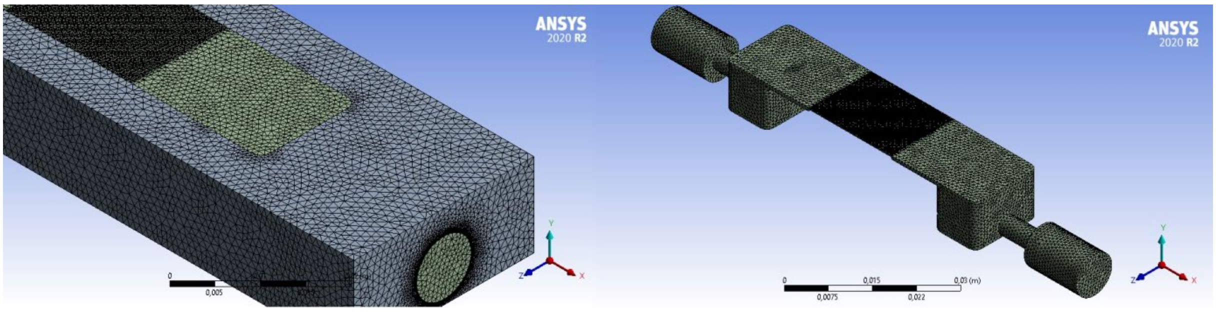

Figure 3. A view of the utilized grid for both analyzed cases.

The convergence occurred for meshes with 511.09k elements for Case 1 and 490.15k for Case 2; the finer mesh was achieved when residuals were less than 10^{-5} for continuity equation and 10^{-6} for momentum and energy equations in both cases. The simulations used the SIMPLE algorithm for pressure-velocity coupling.

A study over the grid dependency was conducted based on wall temperature as a criterion to ensure the results are independent of the mesh. This analysis consisted of three different meshes (around 120k; 370k; 550k elements), aiming to obtain a heated wall temperature range of a maximum of 1.2 K (less than 10% of the maximum wall temperature, according to [6]), it was noticed that the difference in wall temperature was around 1.2 K between the last two meshes. Hence, the mesh chosen aimed to save computational time.

3 Results

Figure 4 presents the numerical heat transfer coefficient for Cases 1 and 2 as a function of mass flux; moreover, the experimental data is included for comparison. The staggered diamond shape pin-fins present a higher heat transfer coefficient; consequently, we can infer that the temperature on the heated wall decreases as the mass flux values increase [7].

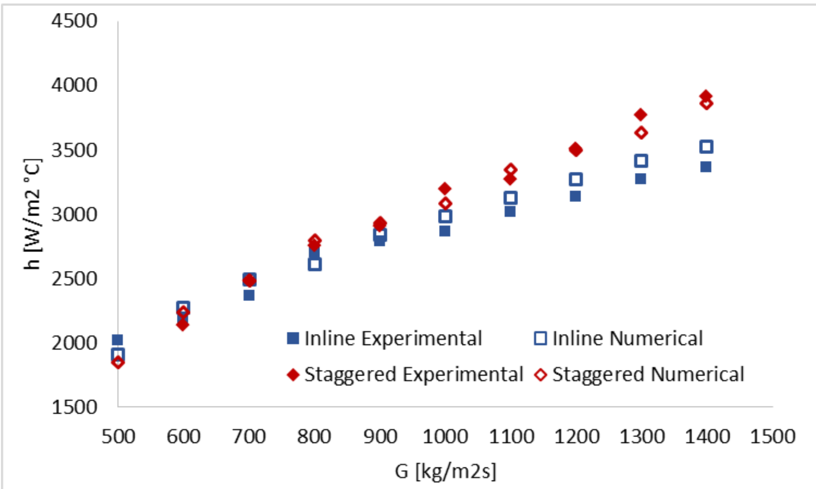

Figure 4. HTC variation with mass flux for the in-line and staggered arrangement.

Figure 4 shows a rise in the HTC for both cases analyzed, considering experimental and numerical results; changing the pin fin's geometry can lead to more effective heat transfer coefficients [8]. The numerical approach and experimental data show satisfactory agreement; the mean absolute error, considering both cases, was about 3.1%.

The staggered diamond shape pin-fins cause a reduced disturbance to the flow, probably due to their diamond shape pin-fins to the flow direction., producing smaller pressure drop than the in-line square shape pin-fins, as shown in Figure 5. For the numerical approach, the pressure drop in the staggered arrangement was, on average, 33% lower than in the in-line arrangement; the same behavior is found for the experimental data (reduction of, on average, 32%).

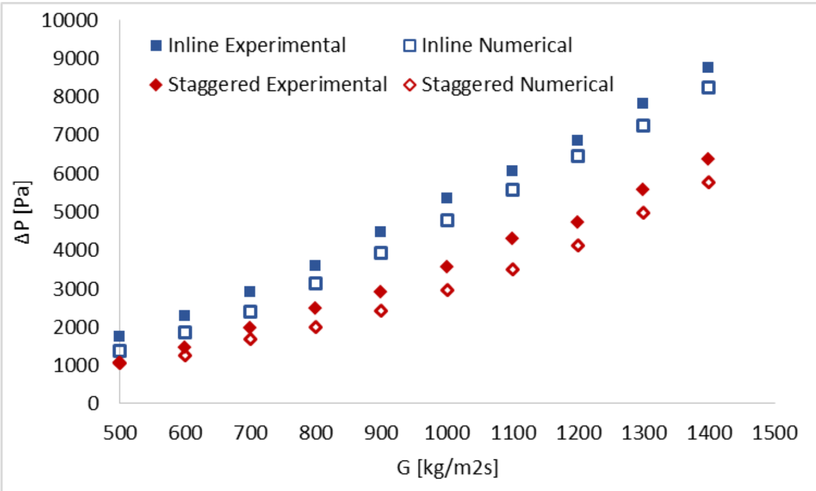

Figure 5. Pressure drop variation with mass flux for the in-line and staggered arrangement.

4 Conclusions

The current study computationally examined the thermal and hydraulic performances of different micro pin-fin heat sinks using a dielectric fluid (HFE-7100) for different operating conditions. The numerical results were compared with experimental data from the research group; the database consisted of heat transfer and pressure drop data obtained using the same working fluid, operating conditions, and geometries.

Considering the numerical results, the staggered diamond shape pin-fins showed a reduction in wall temperature of around 4.6% compared to the in-line square shape pin-fins. The computational results were consistent with the experimental data for the heat transfer coefficient; for both Case 1 e Case 2, the MAE (Mean Absolute Error) was around 3.1%.

A lower pressure drop occurs when staggered diamond shape pin-fins are used as heat sink geometry. This improves the proposed system and has no negative impact on the pumping power systems. The reduction in pressure drop is around 30% for experimental data and numerical approach.

The heat transfer coefficient is improved for staggered diamond shape pin-fins. Such enhancement in efficiency is, on average, 8% higher than the in-line arrangement, which may be due to the higher number of pin-fins improving the heat transfer rate.

Therefore, the present work numerically and experimentally shows that the staggered diamond shape pin-fins geometry is an effective way of cooling, and its application in microscale systems can guarantee efficient cooling for aerospace and electronic devices.

Acknowledgments. The authors are grateful for the financial support from the PPGEM – UNESP/FEIS, the National Council of Technological and Scientific Development of Brazil (CNPq grant number 458702/2014-5), and FAPESP (grants numbers 2013/15431-7 and 2019/02566-8).

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