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Computational Fluid Dynamics Analysis Of Mesh Independence In A Microchannel Heat Sink Model

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Microchannel heat sinks are widely used in electronic cooling applications due to their high heat removal capability and compact structure. In Computational Fluid Dynamics (CFD) simulations, mesh quality significantly influences the accuracy, stability, and reliability of numerical results. Therefore, this study presents a mesh independence analysis of a microchannel heat sink using ANSYS Fluent under steady-state conditions. A three-dimensional heat sink model was developed based on a standard microchannel configuration, and mesh size was selected as the primary variable while all other simulation parameters were maintained constant. Three different mesh resolutions, namely coarse, medium, and fine meshes, were generated with an initial element size of 0.0003 m and evaluated through a series of simulations. The effects of mesh refinement on convergence behaviour, numerical stability, and temperature distribution were investigated. Residual plots and contour results were analysed to determine the influence of mesh density on solution accuracy. The results indicate that finer meshes provide more detailed and stable thermal predictions, while coarse meshes may introduce deviations in the numerical solution. However, beyond a certain level of refinement, the variation in simulation results becomes negligible, indicating that grid independence has been achieved. The study demonstrates the importance of conducting mesh independence analysis to ensure reliable CFD simulations while achieving an appropriate balance between computational cost and solution accuracy for microchannel heat sink applications.

Keywords: Computational Fluid Dynamics, Mesh Independence, Microchannel, Heat Sink

1. INTRODUCTION

A microchannels heat sink is a thermal management system that is widely used due to its ability to improve heat transfer for compact electronic devices. Its high surface area to volume ratio provides good cooling performance and makes them suitable for use in microprocessors, power electronics and high-performance computers as they continue to become smaller and more powerful [1,2]. Cooling techniques will become increasingly important in order to maintain the thermal reliability and operational performance of electronic devices as they continue to be developed and produced over time [3].

The effective numerical modelling to predict microchannel heat sink performance is essential. Much of the analytical work performed on heat sinks, such as Computational Fluid Dynamics or CFD analysis, is done through CFD for accurate calculations of how liquids or gases flow and transfer heat through microchannel geometries. CFD provides a cost-efficient means to estimate the temperature distribution, flow characteristics, and heat transfer performance of various microchannel heat sink designs and/or operating conditions without conducting large amounts of expensive experimental work [7]. Therefore, CFD can be advantageous in enabling researchers to effectively evaluate several alternative designs of microchannel heat sinks before they conduct large experimental tests. Consequently, researchers may be able to save money and time developing new microchannel heat sinks while achieving better performance from those designs.

A major factor in CFD simulation that affects the accuracy and stability of numerical results is the quality of the mesh used for simulation purposes. Discretization of the governing equations into small control volumes is highly sensitive to the level of refinement in the mesh; more refined meshes will better represent an actual physical domain. If a mesh is too coarse, it may not adequately capture important geometric and physical features of the problem being solved. Conversely, if a mesh is too finely refined, the computational cost of the solution will increase but there will be little or no improvement in the accuracy of the resulting numerical solution [4,5]. Consequently, a mesh independence study must be conducted in order to quantify that a numerical solution does not depend upon size of mesh and provide for reliable results [6].

In this study, a microchannel heat sink geometry obtained from a reference design is used. The geometry remains constant throughout the analysis, and only the mesh size is varied. The focus of this work is to evaluate the effect of mesh resolution on numerical consistency, convergence behaviour, and solution stability rather than to analyse detailed thermal performance. Three mesh configurations are investigated to determine the optimal mesh size that provides accurate results while maintaining reasonable computational efficiency.

2. LITERATURE REVIEW

Due to their high ratio of surface area to volume and their superior ability to transfer heat, microchannel heat sinks are among the most effective means of cooling high power electronics [8]. As the power density of modern electronic components continues to increase, efficient thermal management of these components will be critical to avoid overheating and to ensure reliability within the system. Recent research has shown that microchannel heat sinks can dissipate substantial quantities of heat and have enough compactness to be appropriate for usage in electronic packaging [9,10]. In addition, advances in microfabrication technology have also allowed for complex microchannel geometries to be developed which improve the efficiency of heat transfer while maintaining compactness [11].

Microchannel heat sinks are a well-understood application of Computational Fluid Dynamics (CFD). CFD helps to perform a thorough analysis of fluid flow and thermal distribution while minimizing the need for expensive experimental research [12]. Researchers have used numerous numerical simulations and experimental means to conduct research on many different geometries of microchannels and the thermal performance of numerous cooling techniques under differing operating conditions effectively [13,14]. Consequently, designers have adopted CFD as an integral part of the design and optimization process for thermal management systems.

CFD simulations are very reliant upon the discretization of the computational domain using numerical methods and the generated mesh quality [15]. One of the most critical impacts regarding the reliability of CFD results is the mesh quality. An insufficiently fine mesh will inadequately capture steep temperature gradients and flow variation within microchannels; conversely, an overly fine solution will result in substantially longer computational times without meaningful improvement in solution accuracy [16]. As such, it is necessary to reach an optimal compromise between computational efficiency and numerical accuracy.

To verify the independence of simulation results from mesh resolution, researchers frequently carry out mesh independence studies. These involve comparing results from various levels of mesh density and determining when further refinement no longer produces substantially different values for the parameters of interest [17]. The verification of grid independence is an essential component of CFD validation because it reduces numerical error and increases confidence in the results [18]. Additionally, Roy [15] has stated that numerical verification methods are essential to maintain discretization error levels within an acceptable range.

Twenty-three studies have evaluated the computational thermal-hydraulic performance of microchannel heat sinks using surface-enhanced designs or microchannels as the flow passage for a heat exchanger. For example, Singupuram [10] noted that geometric parameters of a microchannel have a large impact on the overall performance heat transfer enhancement as well as fluid flow characteristics. McCormack et al. [19] demonstrated that different spatial dimensions of microchannels affect both cooling performance and pressure drop characteristics. Sterr et al. [20] stressed that uncertainty quantification and mesh size analysis must be conducted in order to yield reliable results from computational simulations to generate good numerical models of microchannel performance. These observations support the notion that numerical modeling of microchannel heat sinks must accurately replicate physical processes if correct and reliable performance evaluation of microchannel heat sinks occurs. The applications of microchannels as an effective means of implementing heat sinks are now being tested on complex high technology electronic devices and three-dimensional integrated circuits (3D ICs).

Patil and Suma [21] suggested that, in order to maintain reliability and lifetime in stacked electronic systems, there is an important need for proper thermal management of the components that will be involved in generating heat during operation. A similar conclusion was reached by Alnaimat [11] regarding the thermal and hydraulic performance of the channels within a microchannel heat sink, indicating that the thermal and hydraulic performance of a microchannel heat sink are affected by channel geometry and operating conditions. In previous work, Qu and Mudawar [13] established a set of benchmark experimental and numerical data for microchannel heaters and were among the most popular experimental and reference studies for the field. More recently, Kandlikar [22] stated that microchannel design optimization would support applications where significant amounts of heat are generated.

In general, investigations performed prior to this study have indicated that the geometry, operating conditions, and numerical modelling method can affect the performance of a microchannel heat sink. While many researchers have concentrated on enhancing heat transfer performance and decreasing thermal resistance [8,9,10,11], there are fewer studies focused on mesh independency and stability of the numerical method. Therefore, this study focuses on the evaluation of the impact of mesh resolution on the convergent behaviour of numerical solutions, the consistency of numerical results, and the accuracy of numerical results. Ultimately, the detailed mesh independency analysis will allow identification of the mesh configuration with the lowest computational cost while achieving a high level of mesh resolution.

3. METHODOLOGY

3.1. Simulation Workflow

The following figure provides an example for the ANSYS Workbench process in this project. There are three types of mesh used in the analysis is coarse, medium, and fine mesh, and each type of mesh is associated with an individual Fluent solver. As such, each mesh type provides an independent simulation; therefore, a consistent analysis can be performed by using different mesh sizes to evaluate grid independence.

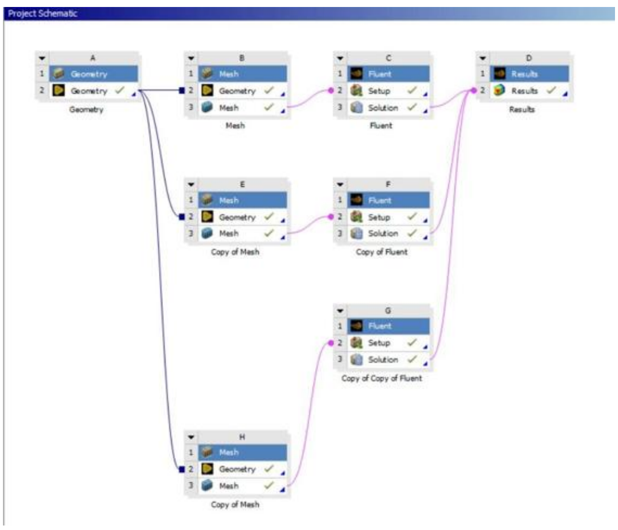

Figure 1. ANSYS Workbench project schematic showing the simulation workflow for different mesh configurations of the microchannel heat sink

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Fluent solver. As such, each mesh type provides an independent simulation; therefore, a consistent analysis can be performed by using different mesh sizes to evaluate grid independence.

3.2. Geometry

The geometry created for this study was a three-dimensional microchannel heat sink created using ANSYS DesignModeler. This model consists of a square base plate and array of uniformly spaced fins on the base plate which create parallel microchannels for dissipating heat. The geometry used was based on a reference microchannel heat sink template and served as the baseline model throughout the mesh- independence analysis performed during this study.

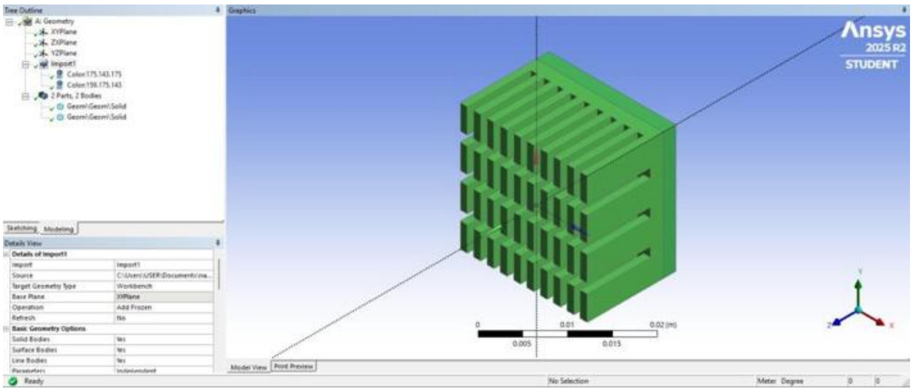

Figure 2. Microchannel heat sink geometry model

The heat sink base feature was developed by creating a profile of a square with dimensions of 0.020 m × 0.020 m, which was then extruded 0.002 m into thickness. Rectangular fins were then created by placing them on the top side of the base plate. The fins were drawn to length with dimensions of 0.003875 m and thickness of 0.0011 m; they were extruded to a height of 0.010 m. A linear pattern operation was then performed in both directions to create an equal fin arrangement throughout the surface area of the heat sink.

The resulting geometrical shape contains a total of 40 rectangular fins evenly spaced apart on the heat sink base plate. Therefore, resulting in multiple flow channels between adjacent fins. These channels result in increasing the overall effective heat transfer surface area and enhance the thermal performance of the heat sink. The geometry was not modified during any of the numerical simulations, only the mesh size was varied for each of the mesh independence studies, thereby ensuring that the differences in the numerical results could only be attributed to mesh refinement and not to any geometric changes.

3.3. Mesh Generation

The mesh generation process was carried out using ANSYS Meshing to discretize the computational domain of the microchannel heat sink. A structured mesh was generated using the MultiZone meshing method, which is suitable for geometries containing regular and sweepable regions. This approach provides better element quality and numerical accuracy compared to unstructured meshes.

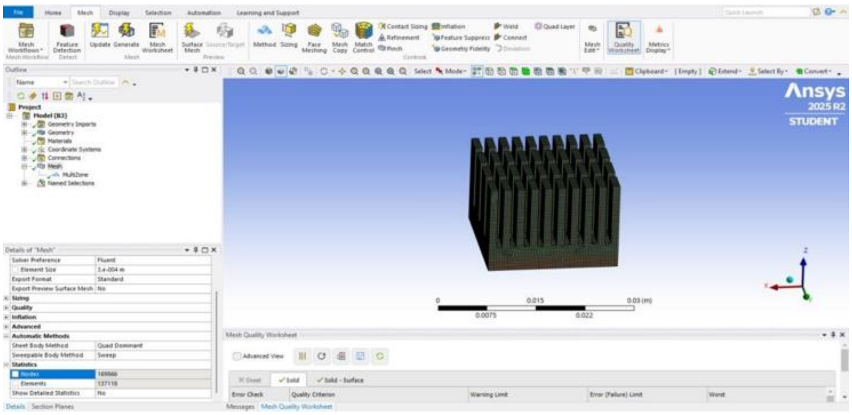

Figure 3. Fine mesh configuration of microchannel heat sink with element size of 0.0003m

As shown in Figure 3, a structured hexahedral-dominant mesh was successfully applied throughout the geometry, including the base plate and rectangular fins. An element size of 0.0003 m was used, resulting in a total of 169,866 nodes and 137,118 elements. The structured mesh distribution provides good coverage of the fin surfaces and flow passages, allowing the geometric features of the heat sink to be accurately represented. The mesh quality is suitable for numerical analysis as it offers a balance between computational efficiency and solution accuracy, ensuring reliable prediction of heat transfer behaviour within the microchannel heat sink.

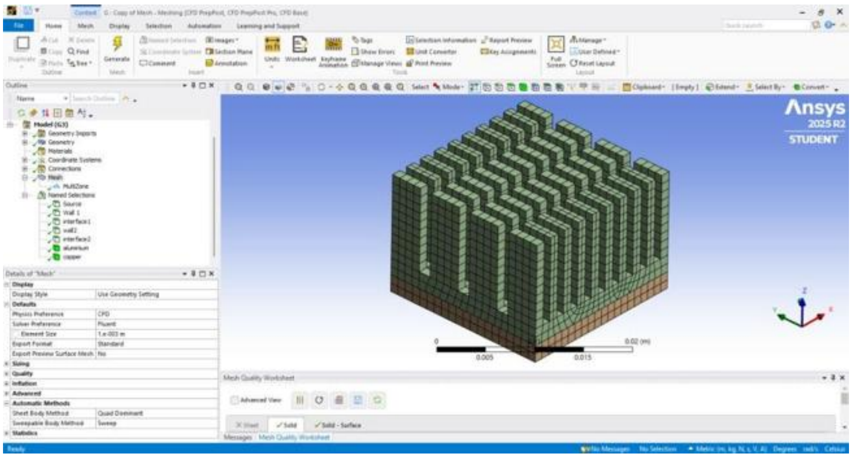

Figure 5. Coarse mesh configuration of microchannel heat sink with element size of 0.001 m

As shown in Figure 5, an element size of 0.001 m was used, resulting in a total of 8,083 nodes and 4,875 elements. Compared to the medium and fine mesh configurations, this coarse mesh contains fewer computational cells, reducing the simulation time and computational resources required. Although the overall geometry of the heat sink is represented adequately, the mesh resolution around the fin surfaces and flow passages is less detailed. Consequently, this mesh configuration may provide lower solution accuracy when predicting temperature gradients and heat transfer characteristics. Nevertheless, the coarse mesh was included in the mesh independence study to evaluate the influence of mesh density on numerical results and to determine whether further mesh refinement is necessary.

3.4. Grid Independence Test (GIT)

A grid independence test was conducted using three mesh resolutions (coarse, medium, and fine) to assess the consistency of the numerical solution. Since no active flow was applied in this simulation, the comparison was based on convergence behaviour and solver stability rather than physical parameters such as velocity or pressure. The mesh is considered independent when further refinement, particularly from medium to fine mesh, results in negligible changes in solution behaviour.

Table 1. Mesh statistics for different mesh resolutions.

Mesh	Element size (m)	No. of elements	No. of nodes
Coarse	0.001	4875	8083
Medium	0.0006	19537	28121
Fine	0.0003	137118	169866

3.5. Boundary Conditions

In typical microchannel heat sink CFD simulations, velocity inlet, pressure outlet, and heat flux boundary conditions are applied to model fluid flow and heat transfer. However, in this study, no flow-driving condition was defined, meaning the fluid remains stationary and no velocity field is generated. This approach was intentionally adopted to focus on numerical accuracy and mesh consistency rather than evaluating actual flow or thermal performance. As a result, the simulation is used to assess mesh quality and solver behaviour instead of representing the real operating performance of the heat sink.

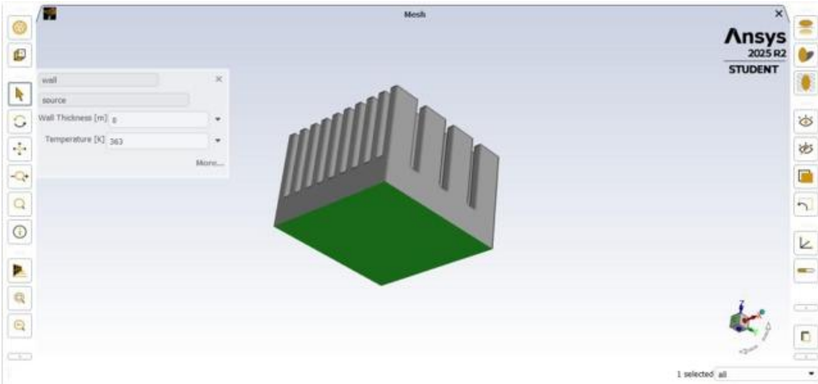

Figure 6. Constant Temperature Boundary Condition Applied to the Bottom Surface of the Microchannel Heat Sink

A constant temperature boundary condition of 363 K was applied to the bottom surface of the microchannel heat sink, representing the heat source from an electronic device. This thermal load allows heat to conduct through the copper base and aluminium fins, enabling the temperature distribution and heat transfer performance of the heat sink to be evaluated under steady-state conditions.

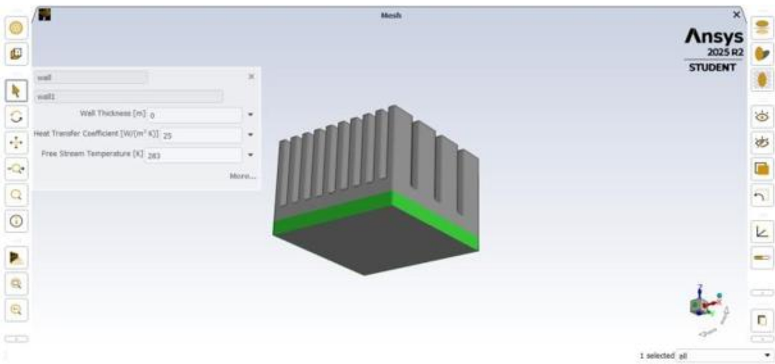

Figure 7. Convection Boundary Condition

A convection boundary condition was applied to the external surfaces of the heat sink with a heat transfer coefficient of 25 W/m²K and an ambient temperature of 283 K. This condition represents heat dissipation from the heat sink to the surrounding environment during steady-state operation.

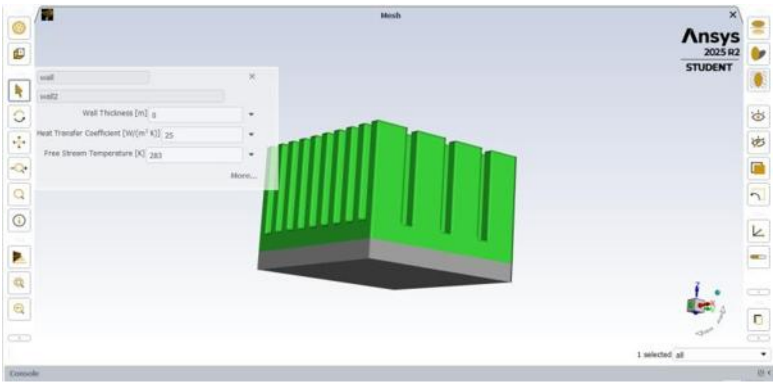

Figure 8. Convection Boundary Condition Applied to the Fin Surfaces

A convection boundary condition was applied to the fin surfaces and outer walls of the microchannel heat sink with a heat transfer coefficient of 25 W/m²K and an ambient temperature of 283 K. This condition allows heat to be transferred from the heat sink to the surrounding environment through natural convection.

Table 2. Summary of thermal boundary conditions for different zones

Zone	Material	Condition Type	Temperature	h (W/m²·K)	T∞ (K)

			(K)		
Source	Aluminium	Temperature	363	–	–
Source	Aluminium	Convection	–	0	300
Wall1	Aluminium	Temperature	300	–	–
Wall1	Aluminium	Convection	–	25	283
Wall2	Copper	Temperature	300	–	–
Wall2	Copper	Convection	–	25	283

4. RESULTS AND DISCUSSION

4.1. Residual Convergence Behaviour

All simulations converged successfully, as shown by the residual plots for the three mesh configurations. Although the maximum number of iterations was set to 460, convergence was achieved much earlier as the residuals dropped to sufficiently low values. The smooth and steady decrease in residuals, without oscillation or divergence, indicates good numerical stability and an appropriate solver setup. The coarse mesh converged faster due to its lower number of elements, while the medium and fine meshes required slightly more iterations because of their higher computational cell count. Overall, the consistent convergence behaviour across all meshes confirms that they are suitable for comparison in the mesh independence study.

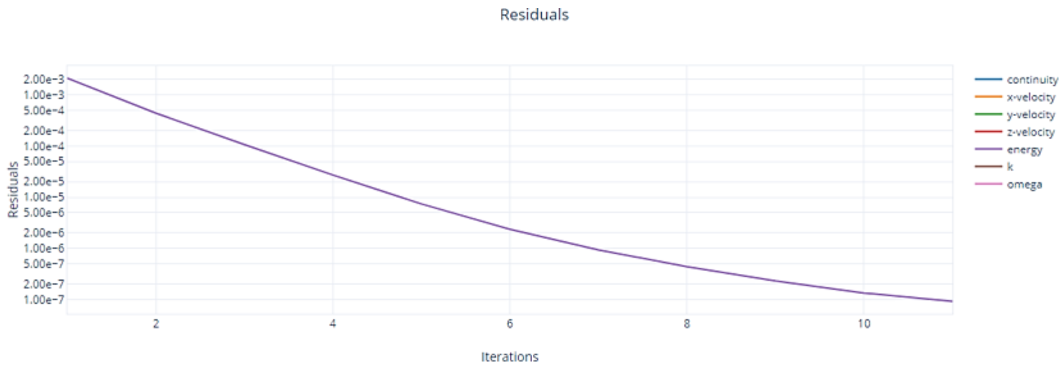

Figure 9. Residual convergence plot of the 0.0003 mesh size

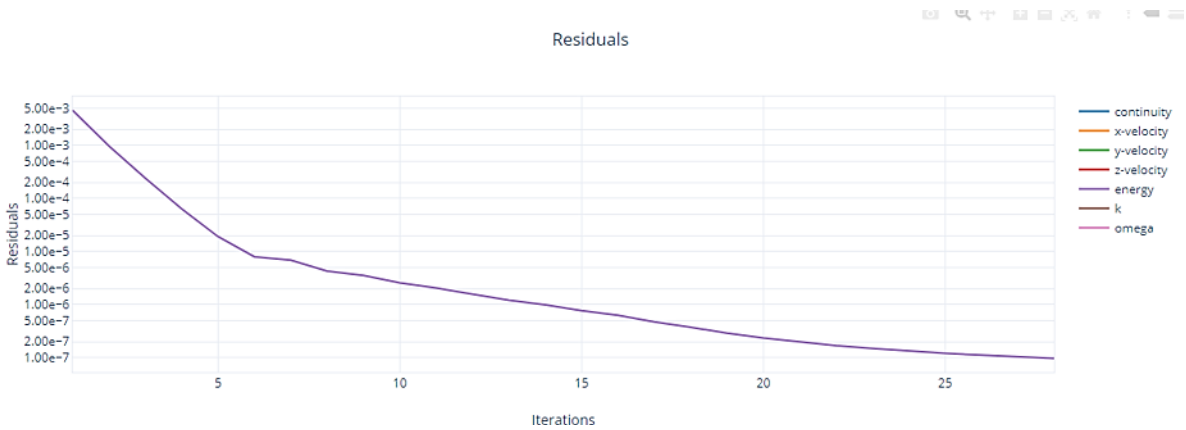

Figure 10. Residual convergence plot of the 0.0006 mesh size

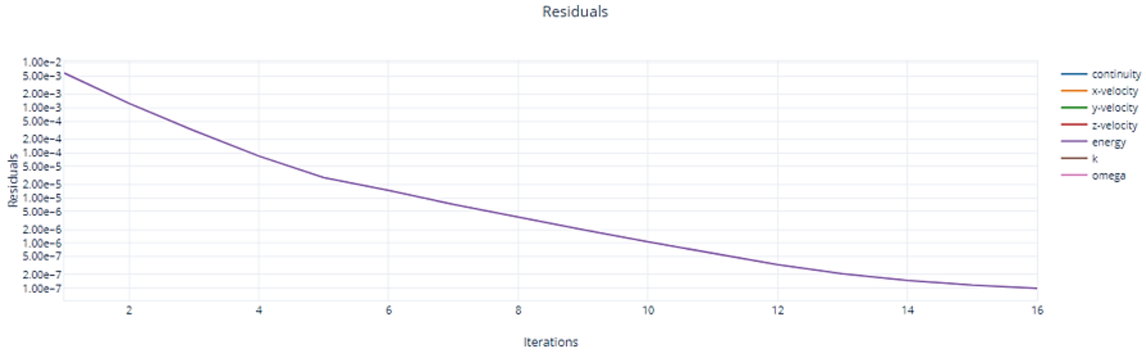

Figure 11. Residual convergence plot of the 0.001 mesh size

4.2. Temperature Distribution

The temperature contours show a similar pattern for all three mesh sizes, with the highest temperature at the base and a gradual decrease along the fins. This reflects heat conduction from the base toward the fin tips. The coarse mesh produces a less detailed distribution due to its larger elements, while the medium and fine meshes give smoother and more refined contours. Although the fine mesh shows the clearest gradient, its overall pattern is very similar to the medium mesh, indicating that further refinement has little effect on the temperature distribution.

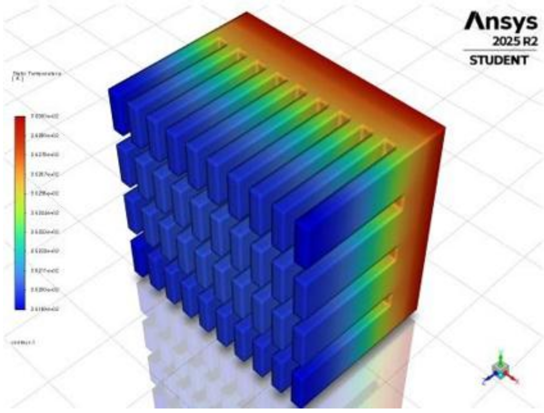

Figure 12. Temperature contour of the microchannel heat sink for 0.0003 mesh size

The fine mesh provides the most detailed temperature distribution among all mesh configurations. The temperature contours exhibit smooth transitions throughout the heat sink geometry, allowing local thermal gradients near the fin surfaces and corners to be accurately captured. The highest temperatures remain concentrated near the heat source region, while the fin surfaces maintain lower temperatures due to effective heat dissipation. The increased number of nodes and elements improves the numerical accuracy of the simulation and reduces discretization errors. However, this improvement is achieved at the expense of longer computational time and higher memory requirements.

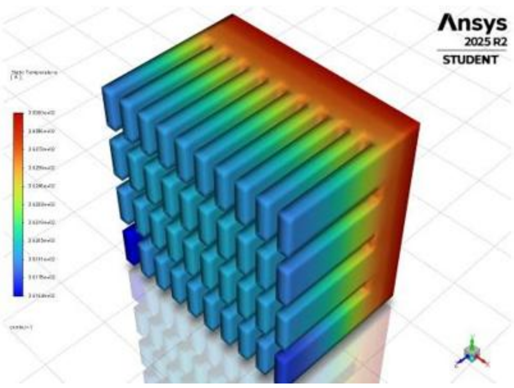

Figure 13. Temperature contour of the microchannel heat sink for 0.0006 mesh size

The medium mesh produces a smoother and more refined temperature distribution compared to the coarse mesh. The temperature gradient from the heat source to the fin surfaces is more clearly represented, indicating improved numerical resolution. Heat is conducted through the heat sink base and distributed along the fins before being dissipated to the surrounding environment through convection. Compared to the coarse mesh, the medium mesh captures the thermal behaviour more accurately while maintaining a reasonable computational cost. The contour demonstrates a balanced representation between solution accuracy and simulation efficiency.

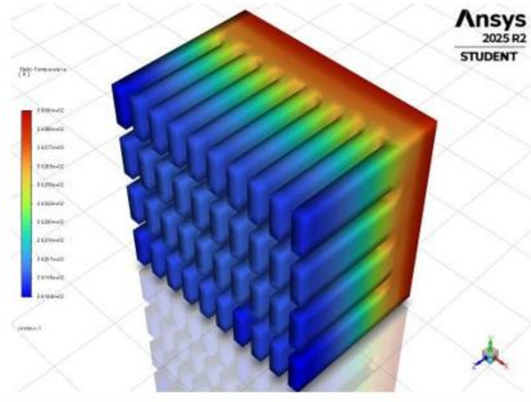

Figure 14. Temperature contour of the microchannel heat sink for 0.001 mesh size

The temperature contour obtained using the coarse mesh shows a clear temperature gradient across the microchannel heat sink. The highest temperature is concentrated near the heat source region, indicated by the red colour, while the lowest temperature is observed at the fin surfaces, represented by the blue colour. Although the overall heat transfer trend can be identified, the temperature distribution appears less detailed due to the lower mesh resolution. The larger element size limits the ability of the model to accurately capture local temperature variations around the fin surfaces and edges. As a result, the coarse mesh provides a faster computational solution but may reduce the accuracy of the predicted thermal behaviour.

5. CONCLUSIONS

This study carried out a mesh independence analysis of a microchannel heat sink using three mesh sizes: coarse (0.001 m), medium (0.0006 m), and fine (0.0003 m). All simulations converged successfully, with residuals decreasing smoothly to low values before reaching the maximum number of iterations, indicating good numerical stability. The coarse mesh converged faster due to fewer elements, while the medium and fine meshes required slightly more iterations because of their higher computational cost.

The temperature contours showed a consistent pattern across all mesh sizes, with heat concentrated at the base and gradually decreasing along the fins. Although the fine mesh provided a more detailed temperature distribution, its results were very similar to the medium mesh. This indicates that further refinement does not significantly improve the solution. Therefore, the medium mesh is considered the most suitable as it provides a good balance between accuracy and computational efficiency.

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