CFD-Based Investigation of Thermal Behavior in Microchannel Heat Sinks using Supercritical CO2

Ajeet kumar [1] *, Harpreet Singh Lubana [2]

[1] *Research Scholar, Department of Mechanical Engineering, Chandigarh University, Gharuan, Mohali, Punjab, India*

[2] *Associate Professor, Department of Mechanical Engineering, Chandigarh University, Gharuan, Mohali, Punjab, India*

Abstract:- Microchannel heatsinks (MCHSs) are a promising technology for cooling high-power electronic devices. Because of its superior thermophysical qualities, supercritical carbondioxide (sCO_2) is a coolant that has potential to replace water in MCHSs.. This paper presents a CFD-based investigation of the thermal behavior in MCHSs using sCO_2 and comparing it with water. It includes the impact of operating and geometric parameters on thermal resistance, temperature of the heat source, and pressure drop. The results show that sCO_2 can achieve better thermal performance than water in certain operating and geometric conditions. For example, by supplying constant heat flux of 1.81×〖10〗^6 W/m^2, sCO_2 is capable of reducing thermal resistance upto 30% compared to water. However, sCO_2 also has a higher pressure drop than water, which can lead to higher pumping power requirements. Overall, the study reveals that sCO2 is a promising coolant for MCHSs, especially for applications where high heat flux removal is required. However, careful consideration should be given to the pressure drop and pumping power requirements when designing sCO_2-based MCHSs.

Keywords*: Supercritical carbon dioxide, microchannel heatsink, flow channel, heat transfer, CFD, thermal performance.*

1. Introduction

Tuckerman and Pease [1] did the first pioneering work in the field of microchannel heatsink.. They have experimentally investigated MCHS for high performance VLSI. They concluded that the main barrier to obtaining low thermal resistance was discovered to be the “h” heat-transfer coefficient (Convective) between coolant & substrate. They used chemical etching and sawing method to create the microchannels in silicon wafers with heat sink area of 1cm^2 and width and height of microchannel were 50 to 56 µm and 287 to 320 µm respectively.

When it comes to cooling electronics, using liquid-cooled microchannels has the dual benefits of reducing the substrates' maximum operating temperatures and balancing out temperature variations between them. The cooled micro-channel heatsink (also known as the MCHS) is able to effectively disperse a substantial quantity of heat produced by small electronic devices due to its advantageous ratio of surface area to volume. Furthermore, it was noted that the thermal resistance experienced significant variation based on the channel width, assuming a consistent aspect ratio. This can be attributed to the close proximity of the lower section of the channels to the heat flow. Furthermore, the optimization technique of the rectangular channel MCHS not only aimed to address the thermal resistance concern but also sought to alleviate the resulting pressure drop penalty.

Dehdashti Akhavan et al.[2] did a comparative investigation to assess the thermohydraulics characteristics of MCHS when using s-CO_2 as the coolant as opposed to the conventional coolant, which is water. This was done in order to determine whether or not there was a significant difference between the two. This experiment aims to identify the impact of input temperature, aspect ratio of channel (AR_c), and mass flow rate on the thermohydraulic performance of the MCHS. The findings show that sCO_2 exhibits a higher coefficient of heat transfer (32 percent) and less friction factor than water at input temperatures that are equivalent. This is the case when comparing sCO_2 and water with the same aspect ratios and geometries as one another. The outcomes of their findings illustrate that amount of power that is dissipated by sCO_2 at supercritical conditions depends on the aspect ratio. The findings reveal that compared to water, an aspect ratio of 0.33 displays lower power consumption, whereas an aspect ratio of 10 exhibits higher power consumption. However, when the system is in a subcooled state, the inverse relationship between the aspect ratio and its impact becomes evident.

In order to investigate the phenomena of conjugate transfer of heat and movement of fluid in a microchannel with a uniformly heated bottom wall, J. Khalesi, et al. [3] carried out a numerical analysis. The purpose of their study was to examine the effects of changes in the sCO_2 transport properties, Reynolds number, and operating pressure on transfer of heat and movement of fluid in pseudo-critical region and close to Critical Point (CP). The results of computational research show that, significant shifts in the physical characteristics of sCO_2 located close to the CP have a considerable effect on the channel's thermohydraulic characteristics.

The thermal resistance of the sCO_2 and its impact on the heat transfer coefficient in brazed plate heat exchangers were investigated by Zendehboudi et al. [4] According to the findings, some operational modes have a greater impact on the coefficient of heat transfer than others when rate of mass flow of sCO_2 is increased. Additionally, the impact of water mass flow rate and intake temperature varies across different modes of operation. Additionally, this study validates buoyant force's effects on the heat transfer process and provides novel connections pertaining to this phenomenon. According to the calculations, average absolute relative errors for the novel revealed correlations are for one and two-pass designs are 11.61 percent and 12.82 percent respectively. In addition, the research showed that the frictional pressure drop that occurs within the heat exchangers has a magnitude that falls somewhere in the middle of the spectrum and follows a pattern that shows progression as the Reynolds number grows.

M. Saeed et al.[5] performed a feasibility study to investigate the viability of using sCO_2 as a cooling agent for MCHS in very small electronic

devices. This study presents a comparison of the performance of a standard water-cooled molten chloride salt MCHS system to that of a sCO_2-cooled molten chloride salt MCHS system. To evaluate the thermohydraulic properties of the proposed coolant, a 3D RANS model (knowns as Reynolds Averaged Navier-Stokes) is developed in this work. To accurately represent the sudden changes in the properties of sCO_2, real gas property (RGP) files are employed. The investigation's results show that, in the presence of high flow rates, the use of sCO_2 has the potential to increase the MCHS's thermal efficiency by a maximum of 32%. Additionally, it can significantly mitigate pressure losses, reducing them by up to sevenfold in comparison to MCHS systems cooled with water. The utilization of sCO_2-cooled MCHS has the additional capability of sustaining a consistent base temperature even under overload circumstances, resulting in a noticeable increase of approximately 2.2 times in the MCHS's overall performance. The results of this investigation give a positive picture of the possible use of sCO_2 as a cooling agent in small-scale electronic systems.

Tu, Y.; Zeng, Y. [6] used computational fluid dynamics (CFD) and experimentation to compare and contrast thermohydraulic properties of microchannels cooled by sCO_2 and water. The results demonstrate that, particularly when the C02 is close to the pseudocritical point, microchannels cooled by sCO_2 will result in decrease of lower average surface temperature and increase of average heat convection coefficient. Additionally rate of entropy generation is lower in comparison to the microchannel cooled by water. The present study also examined the influence of channel type, namely a zigzag structure, on both heat transfer and the rate of entropy generation. The findings suggest that the implementation of a zigzag structure in the microchannel leads to an enhancement in heat transmission.

Jahar Sarkar [7] has conducted research with use of sCO_2 as a method of transferring heat within MCHSs, with a particular emphasis on its application in the cooling of power electronics. Using simulation techniques, the goal of this work is to compare the energy and non-energy efficiency of a micro-channel heat sink that uses supercritical CO_2 to a traditional coolant, water. The findings point to a substantial correlation between pressure and temperature of CO_2 inlet and temperature of heat source, thermal resistance, as well as pumping power. The research demonstrates that within a specific range of fluid inlet temperature, sCO_2 exhibits superior performance compared to water, resulting in a maximum reduction of thermal resistance of 30%. The study emphasizes sCO_2's ability to cool power electronic systems, especially in environments with lower average temperatures.

S.A. Jajja et al. [8] looked at how well sCO_2 transferred heat in a microchannel heat exchanger, paying special attention to how it behaved when it was turbulent. The existing body of literature pertaining to sCO_2 heating has predominantly focused on the investigation of macroscale circular channels operating under low heat flux conditions. Experimentation will be used to examine the heat transfer properties of a microchannel under situations of non-uniform heating and non-circular channel geometries. The goal of this effort is to better understand how heat moves through these channels. The test portion is equipped with five parallel channels, while the data analysis employs both two-dimensional and three-dimensional heat transport models. The current research investigated a wide range of experimental factors, such as heat flow, mass flux, lowered pressure, and intake temperatures. The data that was gathered is then contrasted with correlations that belong to turbulent supercritical and subcritical fluid flows.

A numerical study was done on the use of nanofluids as coolants in MCHSs for electronic components by Al-Baghdadi et al. [9]. The significance of efficient thermal management for the durability and dependability of electronic devices is emphasized. Even though it is expected that the use of nanofluids will increase the rate at which heat is lost, this study compares the thermal effectiveness of nanofluids and water as coolants. The findings indicate that water remains the more viable option due to its cost-effectiveness and safety. A CFD model was used in the study to simulate and evaluate the properties of fluid flow and transfer of heat. The results imply that it is crucial to take each coolant's thermophysical properties into account when evaluating performance requirements.

In order to investigate the behaviors of transfer of heat and movement of fluids within an MCHS that integrates microinserts, Shailesh et al. [10] used computational methods. In this investigation, the operating fluid was water, and investigations were done on how inserts and fluid velocity affected the increase transfer of heat. Additionally, their investigation examines the impact of the friction factor. The outcomes of this research provide useful information on prospective methods for increasing the thermal efficiency of MCHSs by using microinserts.

Design as well as performance of annular MCHSs by H.-L. Liu et al. [11] When designing MCHSs, it is essential to take the homogeneity of the substrate temperature into mind. These heat sinks find extensive use in diverse applications such as microchannel reactors, the cooling of electric chips, and fuel cells. The authors provide two innovative designs, namely the MRNH and MRSH, with the aim of enhancing flow dispersion and achieving uniform substrate temperature in MCHSs. The design of the MRNH is characterized by a simplistic configuration, and its performance is evaluated by computational and experimental analysis. The findings indicate that the simulated outcomes align with the experimental findings, demonstrating that the interleaved configuration exhibits superior temperature uniformity in comparison to the sequential configuration. The MRSH design is a modified version of the MRNH configuration, and its performance is being evaluated in comparison to the original MRNH design. The findings indicate that the MRSH design exhibits superior substrate temperature uniformity and reduced thermal resistance in comparison to the MRNH design. The thermal resistances of the MRSH design exhibit an increase as the slant angle is increased. The Nusselt number has a positive correlation with the dimensionless breadth of the oblique channel.

Experimental research on the turbulent convection transfer of heat of CO_2 at supercritical pressure was conducted by R.-N. Xu et al. [12] The research was carried out inside a serpentine vertical microtube, which had particular measurements, such as an 8.01 mm curvature diameter and an inner diameter of 0.953 mm. This study aims to examine and contrast the effects of Reynolds number, heat flux, and flow direction affecting the maximum amount of heat that a straight tube can transfer. For the purpose of determining the temperature's consistent distribution across the wall, an infrared temperature measurement was utilized. According to the results of the trials, the serpentine tube appeared to have a much higher heat transfer efficiency than the straight

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tube. The findings of this study provide important new insights into the ways in which buoyancy and centrifugal forces can affect the amount of heat that is transferred from sCO_2 contained within serpentine tubes.

2. Thermophysical Properties of sCO2

To commence, it is imperative to furnish fundamental elucidations pertaining to supercritical fluids. The critical point, at which the boundary between the liquid and gas phases vanishes, is determined by the critical temperature and critical pressure. Baron Cagniard's research on cannon barrels in 1822 led to the discovery of a substance's critical point [13]. The researcher was able to determine the critical temperature by listening for abrupt breaks in the sound that occurred as a result of the movement of a rolling flint ball contained within cannon that had been hermetically sealed. Beyond this temperature, the clear separation between the gas and liquid phases ceases to exist, resulting in a sole phase behavior of supercritical fluid.

Andrews made a significant contribution in 1875 by uncovering the critical conditions of CO_2. [14] According to the results of the experiment, the critical conditions are 304.05K (30.90^{0}C) and 7.40MPa, respectively. These results are in line with the currently accepted values of 304.1K (30.95^{0}C) and 7.38Mpa, which are displayed in Fig.1.

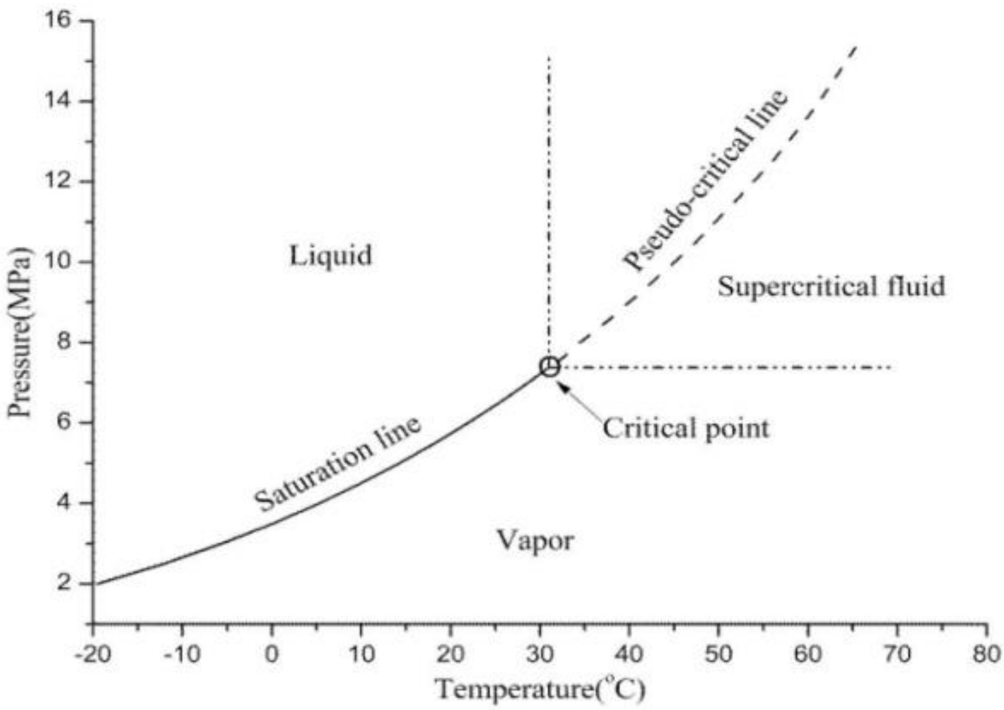

Figure 1 P-T diagram of CO2. [15]

The functional fluid sCO_2 has previously been used in a variety of heat exchangers, including honeycomb UCPHEs (ultra-compact plate heat exchangers)[16] , metal foam tube[17] , power plants based on brayton cycles and PCHEs (printed circuit heat exchangers) as well as combination of both [18]–[25]. However, the research work on MCHSs with the use of sCO_2 as a coolant are very less when compared to water, sCO_2 has better convective heat transfer coefficient due to its reduced viscosity, which also lowers flow resistances and pumping power. The difference between sCO_2 and water's thermal conductivities is actually only one order of magnitude. But sCO_2 has a specific heat capacity that is numerous orders of magnitude more than that of water. When it comes to heat transfer efficiency inside microchannels, this characteristic works in sCO_2's favour[26].

3. Numerical Simulation

It is particularly challenging to effectively characterize and measure heat transfer in MCHSs because of the complex dynamics of fluids and thermal phenomena occurring in microchannels. CFD techniques have historically been used to study the transfer of heat in MCHSs. However, in order to accurately duplicate the complex flow patterns and temperature distributions, these methods frequently require a significant amount of time and computer resources. As a result, it is crucial to develop more effective techniques that can precisely predict the heat transfer efficiency while also lowering the amount of computing resources needed.

To improve the cooling of MCHSs that are subjected to a significant amount of heat flow, researchers are investigating the use of sCO_2 as an alternative to the conventional coolants that are already in use. This is owing to the advantageous thermophysical features exhibited by sCO_2 in close proximity to its critical point. The thermohydraulic effectiveness of a channel within a heat sink designed for sCO_2 is evaluated in this paper using numerical simulations (at a constant pressure of 8MPa). The study also includes a comparison with a traditional liquid coolant, specifically water.

The current investigation involves the computational analysis of the thermohydraulic efficiency of a MCHSs. The inquiry entails the application of two distinct coolants, specifically water and sCO_2, which are customarily and proposedly employed, respectively. According to the authors' understanding, this study serves as the primary exploration of sCO_2 as a cooling agent for MCHSs, including a range of operational parameters such as temperature and pressure.

sCO_2 possesses thermophysical qualities in close proximity to its critical point, rendering it a highly promising contender. Furthermore, the utilization of sCO_2 as a coolant might effectively address the challenges related to traditional liquid coolants .

3.1 Physical Modelling

The schematics of the straight geometry configurations are shown in Fig. 2. The material of this MCHS is Silicon and it contains total 10 microchannels.

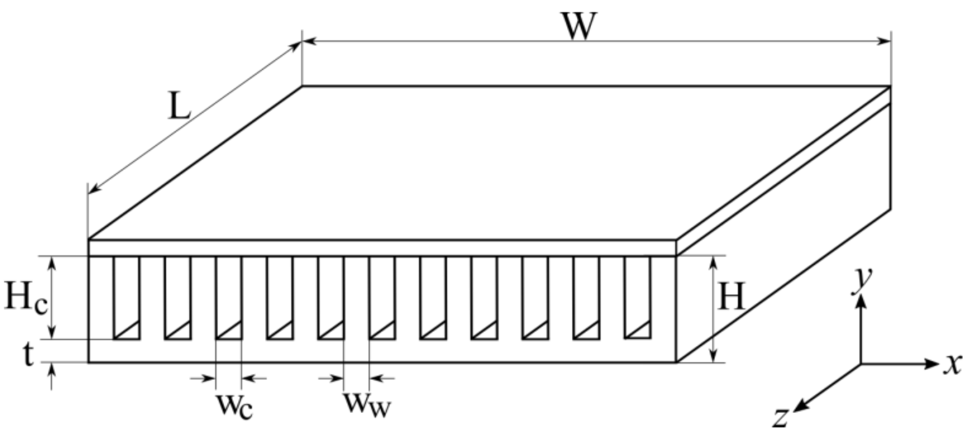

Figure 2: Geometry of Flow Process

The dimensions of the channel is shown in Table-1. The fluid in each channel should be sufficiently uniform, according to the study's assumption on the heat sink design.

L $[\mu m]$	H $[\mu m]$	H_c $[\mu m]$	w_c $[\mu m]$	w_w $[\mu m]$	q'' $[w/cm^2]$
10×10^3	533	320	56	44	181

Table 1:Dimensions

3.2 Boundary Conditions

Supercritical Carbon Dioxide (SCO2):

- Inlet Pressure: 8 MPa
- Inlet Temperature: 308^0 K
- Heat flux: 181 W/cm^2
- Boundary type: Coupled heat transfer at the fluid-solid interface, adiabatic for other solid surfaces

Liquid Water

- Inlet Pressure: 103.42 KPa
- Inlet Temperature: 300^0 k
- Heat flux: 181 W/cm^2
- Boundary type: Coupled heat transfer at the fluid-solid interface, adiabatic for other solid surfaces

3.3 Computational Domain

Numerous channels are stacked in parallel because individual microchannels width (w_c) and corresponding fins(w_w) are smaller than the total heat sink width (W). Therefore, by using the proper symmetry boundary conditions, the computing domain can be reduced to a single repeating module, as illustrated in Figure 3. This method accurately captures the critical thermal-hydraulic properties of the complete heat sink while drastically reducing the computational complexity.

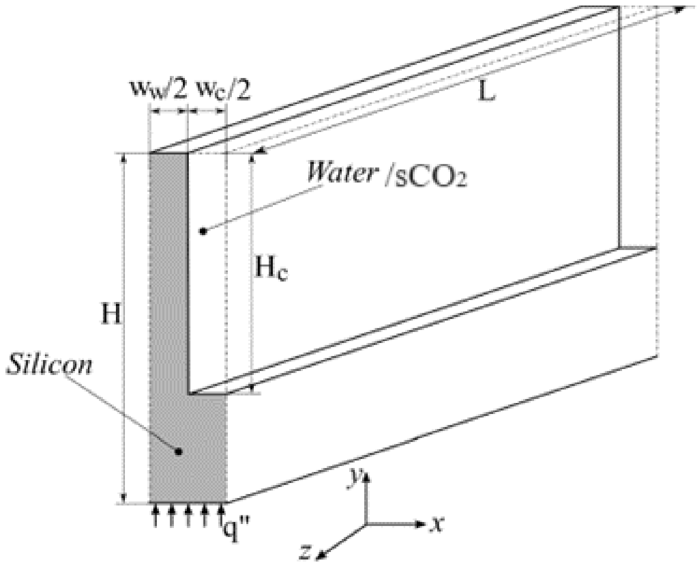

Figure 3: Computational domain

The implified computational domain effectively captures the thermal-hydraulic behavior of the entire heat sink by implementing these symmetry boundary conditions, offering important insights into the performance of the microchannel heat sink.

3.4 Governing Equations

The commercial program ANSYS Fluent is used to solve the governing equations. In order to discretize the equations and solve for the unknown variables (such as pressure, velocity, and temperature) within the computational domain, this software uses the finite volume approach.

The flow and heat transfer phenomena within the microchannel are governed by the following fundamental equations:

Mass Continuity Equation

$\nabla \cdot (\rho u) = 0$ (1)

The net mass flux into any control volume inside the channel must be zero, according to this equation, which expresses the conservation of mass. In this case, u stands for the velocity vector and ρ for the fluid density.

Momentum Equation

$\rho (u \cdot \nabla)u = -\nabla p + \nabla \cdot (\mu \nabla u) + F$ (2)

This formula connects the fluid's rate of change of momentum to the forces acting upon it, thereby embodying Newton's second law of motion. The terms stand for:

- $\rho u \cdot \nabla u$: Convective acceleration
- $-\nabla p$: Pressure gradient
- $\nabla \cdot (\mu \nabla u)$: Viscous stress forces
- F: Body forces (e.g., gravity)

Energy Equation

$\rho C_p (u \cdot \nabla T) = \nabla \cdot (k \nabla T) + Q$ (3)

The conservation of energy within the channel is reprented by above equation. It describes the balance between energy advection, conduction, and internal heat generation. The terms represent:

- $\rho C_p u \cdot \nabla T$: Convective heat flux
- $\nabla \cdot (k \nabla T)$: Conductive heat flux
- Q: Internal heat generation

3.5 Mesh Descriptions & Grid Independence

The meshing process for this investigation was conducted using ANSYS Meshing software. The polyhedra elements were selected based on their ability to accurately depict the primarily laminar flow found in the microchannels, offering both accuracy as well as convergence advantages.

In order to precisely resolve the viscous sublayer and steeper velocity gradients, the mesh density was deliberately varied throughout the domain, with finer elements close to the channel walls. For computational efficiency, larger elements were used in the core region of the channels and in areas where low flow gradients were anticipated.

To ensure the reliability and accuracy of the CFD results, a grid independence test was conducted. Three meshes with progressively increasing element densities were generated: coarse, medium, and fine type. Each mesh was subjected to the same CFD simulation conditions and boundary values.

3.6 Model Validation

Any CFD study must include model validation as a necessary step for ensuring both the accuracy and reliability of the simulation results. The developed CFD model for a comparable microchannel heat sink configuration under the same operating conditions was verified in this work using experimental data as well as the simulation data that was found in the literature.

This investigation's model is validated with experimental data of Tuckerman and Pease [1] and numerical data of Liu and Garimella.[27] The coolant used by above both authors is Water. It is validated with result of the thermal resistance by performing the simulation with water as coolant. The result aligns with the value reported by aforementioned authors.

Authors	Present Study	Tuckerman and Pease	Liu and Garimella

Type of Investigation	Numerical	Experimental	Numerical
Thermal Resistance	0.122 °K/W	0.110 °K/W	0.115 °K/W

Table 2:Model validation

Strong evidence of the precision as well as reliability of the created CFD model is provided by the near agreement between the CFD predictions and experimental data for thermal resistance. The model's capacity to forecast the thermal behavior of microchannel heat sinks with sCO_2 as a coolant is strengthened by this validation process.

4. Result & Discussions

The CFD simulations conducted in the present study successfully analyzed the thermal resistance of a heat sink using both water and sCO_2 as coolants. The results revealed significant differences in heat transfer performance between the two fluids.

The formula used is $R = \frac{\Delta T_{max}}{q'' A_s}$

Where, ΔT_{max} = Difference between inlet temperature (T_i) and final temperature (T_o)

Heat Sink projected Area $A_s = 1 \times 10^{-4} m^2$,

Heat flux at bottom $q'' = 1.81 \times 10^6\ W/m^2$

For water, with an inlet temperature of 300 K and an maximum temperature at outlet of 322.21 K, the resulting thermal resistance was 0.122 K/W. In contrast, sCO_2 at the inlet temperature 308K and an final temperature of 324.655 K exhibited a lower thermal resistance of 0.092 K/W. This translates to a 25% reduction in thermal resistance for sCO_2 compared to water, demonstrating its superior heat transfer capabilities.

These findings align with previous research data. Experimental studies by Tuckerman and Pease [1] yielded a thermal resistance of 0.110 K/W for water, while simulations conducted by Liu and Garimella [27] achieved a thermal resistance of 0.115 K/W. The current study's results for water fall within the range of these established values, confirming the model's accuracy and reliability.

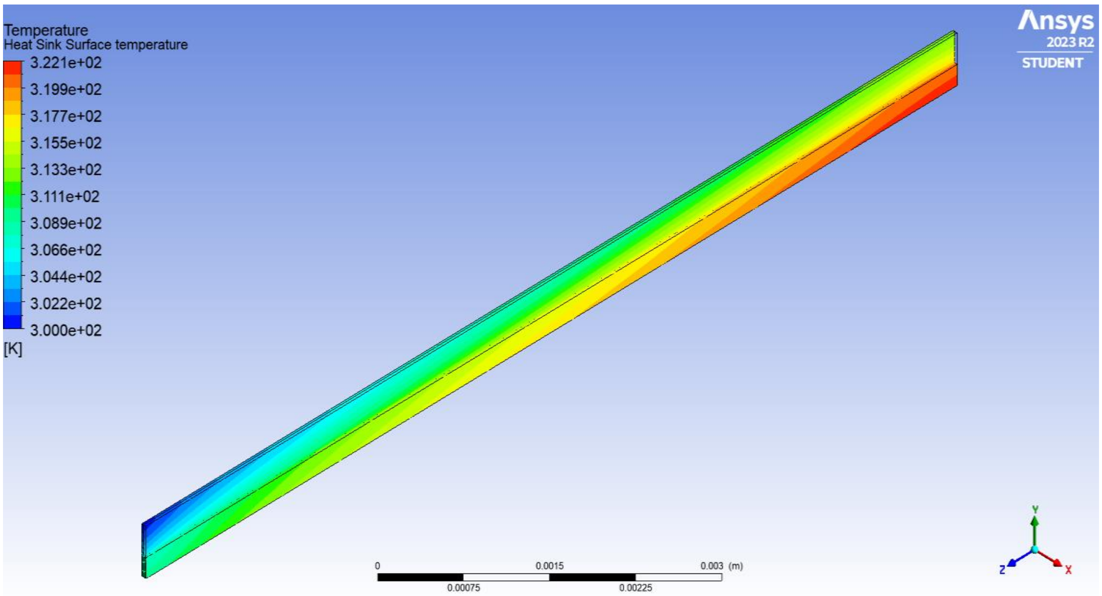

Figure 4: Water - Heatsink surface temperature

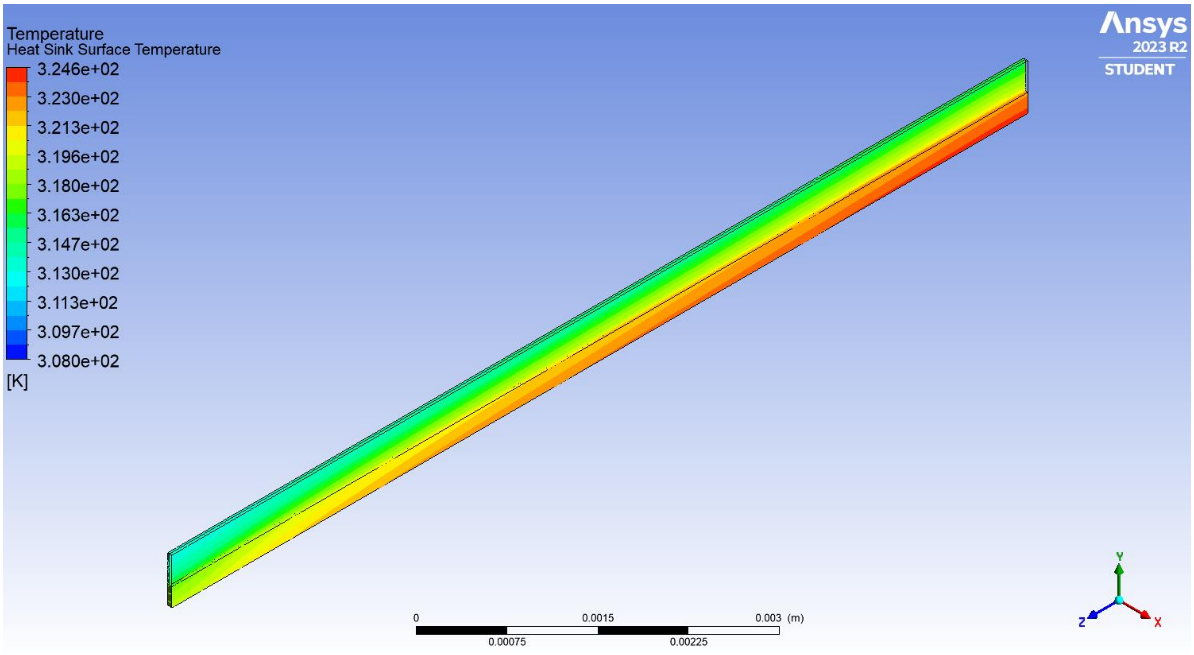

Figure 5: sCO_2 - Heatsink surface temperature

The given simulation diagram shown in Fig. 4 and Fig. 5 shows the heat sink surface temperature variation with coolant used as water and sCO_2 respectively.

The distinct thermophysical properties of sCO_2 are responsible for its superior heat transfer performance. Strong heat conductivity and specific heat capacity near the critical point of sCO_2 result in improved heat absorption and dissipation. Furthermore, the microchannels' effective heat transfer is made possible by its low viscosity.

These results have significant ramifications for high-performance heat sink development and design. Heat sinks can be made substantially smaller and lighter while retaining or even increasing their cooling capacity by substituting sCO_2 for water. Applications like electronics and aerospace engineering, where weight and space restrictions are crucial, will especially benefit from this.

To improve the heat transfer efficiency of sCO_2-based microchannel heat sinks, more research may look into optimizing microchannel geometries and operating conditions. Furthermore, investigating the use of sCO_2 in different cooling systems may result in important developments in thermal management technologies.

5. Conclusion

In summary, this work has effectively examined, using sCO_2 as a coolant, the thermal performance of a microchannel heat sink. According to the CFD simulations, sCO_2 can transfer heat more effectively than water, resulting in a 25% decrease in thermal resistance. The distinct thermophysical characteristics of sCO_2 namely, its high thermal conductivity and specific heat capacity are responsible for this enhanced performance. The results are consistent with experimentally and theoretically established data, which adds to the credibility and accuracy of the used CFD model.

These findings have important implications for the design and development of heat sinks of the future. It is possible to create smaller, lighter heat sinks with better cooling capacities by substituting sCO_2 for water. This is important for applications where weight and space constraints are critical. Subsequent investigations may concentrate on refining microchannel configurations and operational parameters to augment the heat transfer efficacy of sCO_2-derived microchannel heat sinks. Furthermore, investigating the use of sCO_2 in different cooling systems may open the door to important developments in thermal management technologies in a range of industries.

6. Future Work

In order to further improve performance, future work may concentrate on optimizing operating conditions, channel geometry, and the use of sophisticated modeling techniques. Reaching the full potential of this technology will require investigating additional fluids and practical applications.

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