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Optimization and Performance Evaluation of Microchannel Heat Sinks for High-Power Density Applications

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Abstract: Microchannel heat exchangers have been the subject of theoretical investigation. The exchanger's thermal behaviour is predicted by solving the equations of the computational fluid dynamics (CFD) model. Problem geometry and meshing were done in ANSYS Workbench. The models have been solved using the ANSYS Fluent 12.0 solver. This profile is made to fit four distinct geometries. Their shapes are V-shaped, rectangular, convergent, and divergent. The coolant fluid in this case is distilled water. After comparing the present CFD estimated heat transfer coefficient value with the analytical results, it was found to be quite close. The findings demonstrate that in both turbulent and laminar zones, the heat transfer coefficient is enhanced by the addition of distilled water. This study proves the relationship between the heat transfer coefficient and the fluid's thermal conductivity, denoted as h α k. A rectangular microchannel's hydrodynamics and thermal behaviour are examined in this work. Calculations made using ANSYS Fluent for wall temperature change, channel pressure drop, and friction factors provide good predictions for the experimental data. Using pressure, temperature, and velocity contours, its behaviour has also been studied.

Keywords: Micro Channels; Heat Exchangers; Fluent; CFD; Heat Transfer Coefficient; Pressure Drop; Friction Factor; ANSYS Fluent 12.0 Solver.

Introduction

Micromachining has been very popular in the past ten years for creating heat sinks, which are extremely efficient cooling devices. Reduced coolant consumption and smaller dimensions are two of the obvious benefits that have contributed to their increasing popularity [9-12]. Microchannels are one of the most important developments in micromachining technology. Microchannels are crucial to these devices and have attracted a lot of attention from researchers studying fluid flow and heat transfer because of their many uses in engineering and medicine [5]. The presence or absence of boiling within the microchannels determines whether the heat sink is a two-phase or single-phase system. The main factors that dictate these modes of operation are the coolant flow rate and the heat flux through the channel wall. For a constant heat flux, the coolant can stay liquid in all of the microchannels. On the other hand, a two-phase heat sink might occur if the coolant boils at lower flow rates [13-21].

In today's cooling systems, microchannels are crucial. Applications ranging from electronic cooling to biological equipment rely on their capacity to manage large heat fluxes with low coolant volume. Efficient heat removal is essential for high-power device performance and longevity, and microchannels, with their small dimensions, make this possible [22-29]. Microchannels improve heat dissipation in heat sinks by expanding the transferable surface area. Applications like microprocessors and other electronic components, where space limits and temperature management are crucial, benefit greatly from this efficiency. When it comes to studying and creating microchannel heat exchangers, numerical methods are now necessary [30-35]. One particularly effective computer-based numerical technique among these methods is Computational Fluid Dynamics (CFD). Engineers and researchers may examine chemical reactions and other related phenomena, as well as fluid flow and heat transfer behaviour, with great precision using computational fluid dynamics (CFD) [36-41].

Computational fluid dynamics (CFD) uses a system of conservation-law based mathematical model equations to derive flow variables over the computational domain, which are subsequently solved by computer programmes [42-47]. With this method, the fluid dynamics and heat transport mechanisms of microchannels may be understood in great depth. Drying, burning, separating, exchanging heat, transferring mass, reacting, mixing, multiphase systems, and processing materials are all instances of chemical process industries that make use of computational fluid dynamics (CFD) [48-55]. More efficient and dependable systems can be designed with the help of precise models of these processes. To make sure CFD models are accurate and dependable, validation is key. As part of this procedure, we compare the CFD results to the existing analytical, theoretical, or experimental data. If a model fails to pass validation, it needs to be adjusted and retested until it is deemed dependable. Using this iterative method, we can build reliable CFD models for use in analysis and design [56-61].

Research into microchannel flow and heat transfer is crucial for the development of both current and future technological systems. The significance of microchannels' ineffective heat management is crucial, especially given the ongoing trend of downsizing in many industries. Microchannels find widespread application in engineering for the purpose of cooling high-power devices, including power amplifiers and microprocessors [62-71]. Their exceptional heat dissipation capabilities make them perfect for these uses. When it comes to chemical processing, microreactors with microchannels are the way to go for exact control of reaction conditions. Medical professionals utilise microchannels in lab-on-a-chip technologies to analyse and diagnose by manipulating small quantities of fluids [72-81]. Because of their small size and good heat transfer properties, they are ideal for use in wearable and portable medical equipment.

There is a dearth of literature on microchannel heat exchanger performance studies that make use of computational fluid dynamics (CFD) models, in contrast to the mountain of material on microchannels and microchannel heat sinks. Because of this void, we may investigate how CFD could be useful in the process of developing and perfecting these devices. Conjugate heat transfer and microchannel flow are the main topics of this computational fluid dynamics (CFD) study [82-91]. Coupling fluid convection in microchannels with heat conduction in the solid structures containing the fluid is the process of conjugate heat transfer. With this all-encompassing method, the thermal behaviour of microchannel heat exchangers may be more precisely modelled. Building a 3D model of the microchannel heat exchanger is the first step in the computational fluid dynamics (CFD) model. To solve the fluid flow and heat transfer equations, the geometry is discretized into a computer grid. The energy equation for heat transmission and the Navier-Stokes equation for fluid flow are common examples of such equations [92-99].

The model is given the physical conditions of the system by applying boundary conditions. Inlet and exit velocities, pressures, and wall heat fluxes, as well as the thermal characteristics of the fluid and solid materials, may be among these factors. The flow and temperature fields within the microchannels are obtained by running simulations after the model is set up [100-111]. The heat exchanger's efficiency is assessed by examining these outcomes, which include the pressure drop, temperature distribution, and heat transfer coefficient. In order to determine which parameters have the most impact on the efficiency of microchannel heat exchangers, parameter sensitivity analysis is a crucial component of computational fluid dynamics (CFD) investigations. Researchers can experiment with different values for parameters like heat flux, coolant flow rate, and channel diameters to see how these affect the heat exchanger's efficiency and efficacy. The microchannel heat exchanger's performance can be improved by applying optimization techniques to the computational fluid dynamics (CFD) model. To identify the best design parameters for heat transmission, pressure drop, and material cost-minimization, one can use optimization techniques like genetic algorithms. Microchannel heat exchanger analysis and design relies heavily on numerical methods, especially computational fluid dynamics (CFD). More efficient and dependable systems can be designed with the use of CFD, which gives precise insights into the fluid dynamics and heat transfer processes of microchannels [112-119].

For computational fluid dynamics (CFD) models to be accurate and dependable, validation is key. Researchers can build trustworthy models for design and analysis by comparing CFD results with theoretical and experimental data [120. A great deal of hope for improving the efficiency of microchannel heat exchangers lies in the application of computational fluid dynamics (CFD). Parameter sensitivity analysis and optimization methods allow researchers to determine the most important aspects impacting heat exchanger efficiency, allowing them to create designs that optimise heat transfer, minimise pressure drop, and material costs [121-127]. The significance of microchannel's ineffective heat management will continue to rise due to technological advancements and the persistence of downsizing trends. To address the thermal management issues of future technologies, it is essential to keep studying microchannel fluid flow and heat transfer.

Literature Review

The work by Khan and Kim [1] investigated several microchannel forms of heat sinks in a Reynolds number range of 50-500 by numerically evaluating thermal resistance, Nusselt numbers, and friction factors using Navier Stocks equations. For Reynolds numbers up to 300, the inverted trapezoidal shape outperforms the others in terms of thermal performance. Across the whole range of Re, the semi-oval form demonstrates the lowest thermal resistance.

By combining the continuous method with the potential of slip at the borders, Al-Nimr et al. [2] conducted a numerical examination of the hydrodynamic and thermal behaviour of the flow in a parallel plate micro heat exchanger. The research demonstrated that as Kn increases, the velocity slip and temperature jump at the walls also increase.

Morad et al. [3] report five distinct setups in their experiment (circular, hexagonal, rectangular, triangular and straight slot). The most thermally efficient of these five channel entrance designs were found to be the straight and triangle varieties. Meanwhile, the hexagonal had the worst results.

Research by Lin et al., [4], In order to optimise the micro multi-channel heat sink for heat dissipation, the researchers in the study used a numerical package that made use of a genetic algorithm. The situation with a fixed bottom surface thickness offers greater performance for weight reduction in heat sink applications. Assuming the surface on both sides as a design variable, however, allows for exceptional heat removal performance.

(Song et al., [6]], This research presents the design of a microchannel heat sink with a sinusoidal wave shape for active cooling of small electronic devices like insulated-gate bipolar transistors (IGBT). Wavelength, Reynolds number, and amplitude were studied in relation to heat sink transfer. The study's findings are also thought to have practical applications for developing electronic devices with active cooling in the best possible way.

Parallel flow micro heat exchangers subjected to constant external heat transfer were theoretically investigated by Mathew et al. [7] for their thermal performance. The heat exchanger's efficiency and distribution of temperatures are predicted by the model's equations. The model can be utilised when the individual.

(Lu and Chao, 2008) Innovative microchannel heat sinks, including MCHSs with two or more layers, thin films within complicated seals that are both flexible and rigid, and cooling augmentation using microchannels with rotatable separating plates are all compared in this study. Here we offer a comprehensive overview of DL-MCHS and ML-MCHS, including their number of layers, primary features, configurations, pros and cons, heat resistance, and pumping power. At flow Reynolds numbers below certain levels, these DL-MCHS and ML-MCHS offer greater cooling effects per unit of pumping power compared to the rigid ones.

Project Gap

Geometric forms such as rectangles, circles, hexagons, triangles, etc. have been the focus of previous studies. The shapes all showed the same thing: reduced fluid viscosity and thermal efficiency. We are now developing five distinct geometries to address these shortcomings by improving heat conductivity and fluid efficiency. In order to compare the five models' heat-removing capacities to the values of heat exchangers now available on the market, we want to conduct tests. Here, water serves as the working fluid. Nanofluids and other expensive and difficult-to-synthesize coolants have been used in previous efforts. In our project, we managed to overcome that obstacle.

For the surfaces of the non-porous walls, a no-slip boundary condition was applied, where the two velocity components were set to zero, i.e., =vr= 0. There is a steady flow of heat (100 W/m2) onto the wall of the channel. At the centerline, axis symmetry was determined. The channel's inlet was designed to have a consistent entrance temperature and a uniform mass flow. The pressure was noted at the exit.

Method of Solutions

The aforementioned topic can be addressed in two ways: I analytically and (ii) using computational fluid dynamics (CFD). An analytical approach was utilised by Lee and Mudwar in 2007. First, determine if the flow is laminar or turbulent; second, use Eq. 4.2 to get the bulk mean fluid temperature; and last, use Eq. 4.1 to get the wall temperature. This is the procedure for computing the heat transfer coefficient (h). For the specified inlet mass flow rate, the findings of Lee and Mudwar (2007) reveal that the mean and wall temperatures were incorrectly calculated. Analysis of heat transfer coefficient values is thus the focus of the current investigation. It is also possible to compare the two numbers by use CFD methods to get the heat transfer coefficients.

In order to resolve the issue, the CFD approach use the commercial programme ANSYS Fluent 12.0. The convective transport terms are discretized using a pressure correction-based iterative SIMPLE method with a 1st first-order upwind scheme in Fluent's defined solver. All of the dependent variables have a convergence criterion of 0.001.

Material Properties

In this case, the coolant is distilled water. One container is used to boil the distilled water into vapour, while another is used to condense it into liquid. Contaminants in the first water supply that do not evaporate at temperatures below or close to the boiling point of water are retained in the initial container. So, one form of purified water is distilled water.

Within the confines of a rectangular microchannel housed within a test module, this section models the motion of a single-phase fluid. Figure 1 shows the experimental setup that was constructed by Qu and Mudawar (2007) using a test module. Module building for microchannel testing, including placement of thermocouples. Aluminum 6061 is the material used to make the microchannel.

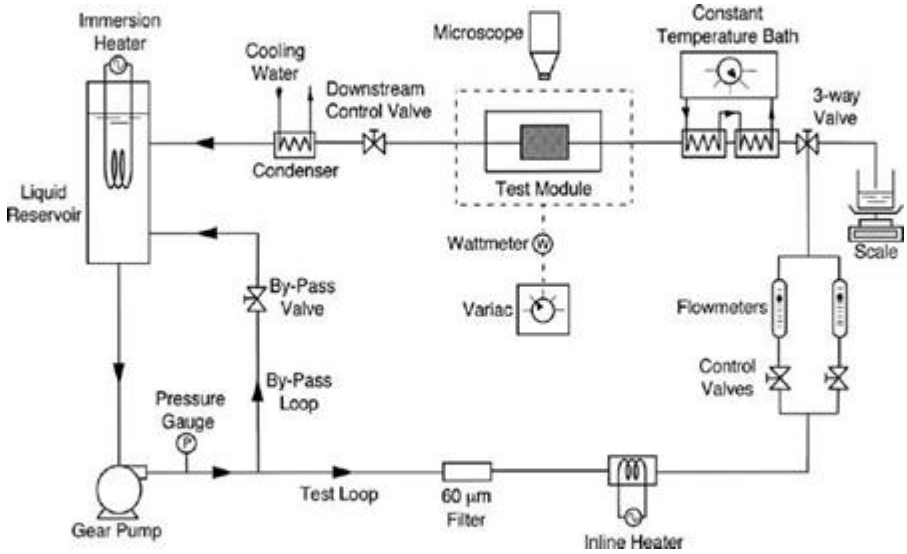

Figure 1: Experimental setup with microchannel test module

This study mimics the experimental work done on the test rig by Lee and Mudawar [8]. A test module contains a rectangular microchannel through which fluid is flowing. Within the module, you'll find twenty-one rectangular micro-channels. The width, depth, and length of each microchannel measure 50 mm. The velocity at the intake is denoted as u (in m/s). Aluminum 6061 makes up the microchannel. Two cartridge heaters, concealed in the base of the test module, supply the heat. The microchannel's upper surface is kept at an adiabatic pressure.

Meshing of The Computational Domain

Figure 2 shows the results of using the structured mesh approach to mesh the geometry. All three-dimensional coordinates were used to generate nodes with an element size of 0.25.

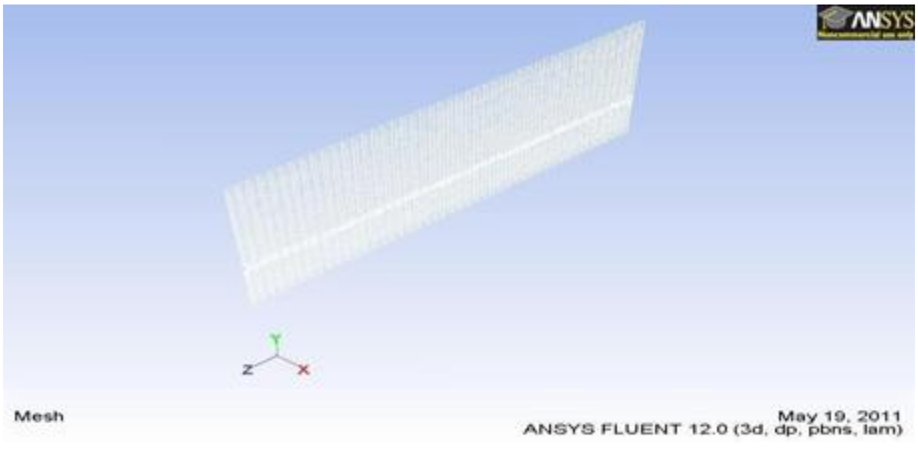

Figure 2: Three-dimensional geometry of rectangular microchannel with structured mesh

The surfaces were given a no-slip boundary condition, meaning that at that boundary, both components of the velocity were set to zero, u = υ = 0. At the channel's entrance, we set a constant inlet temperature and a uniform velocities. The pressure was noted at the exit. Every surface of the walls was given a heat flux. Aside from the bottom sink, every surface of the sink is subjected to adiabatic conditions, meaning that heat flux is zero. Each of the three channels—bottom, left, and right—is given an effective heat flux. There are adiabatic conditions on top of the channel as well. In a heat sink, the Continuum is solid, while in a channel, it is fluid.

For the discretization of convective transport terms, the given solution employs an iterative SIMPLE approach based on pressure correction using a first-order upwind scheme. All of the dependent variables have a convergence criterion of 0.001. Set as default the relaxation factor's values.

Results & Discussion

The test results of the five different channels are given below tables 1 to 5.

Heat Input	100	120	140	160	180
Optimum Heat transfer rate(W/mm^2)	300	400	500	300	400
a c (wc/H c)	0.387	0.273	0.206	0.497	0.38
R min (C/W)	0.076	0.0658	0.0579	0.111	0.0987
T max (c)	36.9	35.5	34.5	41.4	39.8
Pressure Drop (KPa)	45.5	39.85	36.5	17.9	14.85

Table 1: Result for convergent channel

Heat Input	100	120	140	160	180
Optimum Heat transfer rate(W/mm^2)	116	109	103	149	152
a c (wc/H c)	0.387	0.273	0.206	0.0497	0.38
R min (C/W)	0.76	0.0658	0.0579	0.111	0.0987
T max (c)	36.9	35.5	34.5	41.4	39.8
Pressure Drop (KPa)	45.5	39.85	36.5	17.9	14.85

Table 2: Result for divergent channel

Heat Input	100	120	140	160	180
Optimum Heat transfer rate(W/mm^2)	116	106	103	142	146
a c (wc/H c)	0.37	0.265	0.206	0.473	0.365
R min (C/W)	0.0695	0.0617	0.506	0.0985	0.0904
T max (c)	36	35	34.2	39.8	38.7
Pressure Drop (KPa)	47	41.5	37.5	18.5	15.3

Table 3: Result for a rectangular channel

Heat Input	100	120	140	160	180
Optimum Heat transfer rate(W/mm^2)	111	91	100	139	143
a c (wc/H c)	0.363	0.228	0.2	0.463	0.358
R min (C/W)	0.0681	0.05772	0.053	0.097	0.0885
T max (c)	35.8	34	33.9	36.61	38.5
Pressure Drop (KPa)	47	35	37.5	18.5	15.3

Table 4: Result for V-shaped channel

Heat Input	100	120	140	160	180
Optimum Heat transfer rate(W/mm^2)	109	57	58	64	73
a c (wc/H c)	0.187	0.143	0.116	0.213	0.183
R min (C/W)	0.123	0.1	0.108	0.169	0.15
T max (c)	43	41.7	41	48.9	47.38
Pressure Drop (KPa)	83	74	66	34.6	27.4

Table 5: Result for Mesochannel channel

Discussions

The findings demonstrate that, in comparison to other channels, concurrent channels possess superior thermal characteristics. Hence, we may visualise the channels' operation through graphs generated from the acquired values (Figure 3).

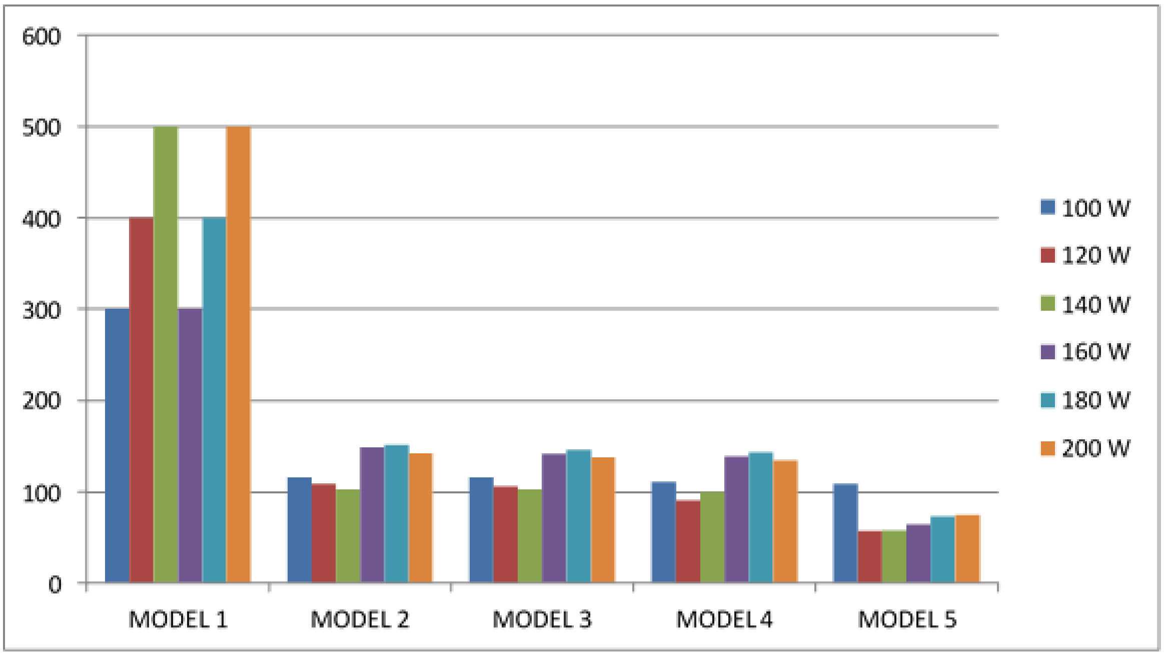

Figure 3: Comparison of various channels

In terms of thermal efficiency, convergent channels outperform all others. All three pieces of test data wall temperature distributions, channel pressure drop, and friction factor were confirmed by the computational result. At the entrance of the microchannel, the heat transfer coefficient is higher. The temperature of the wall rises as one moves from the microchannel's entrance to its exit.

Conclusions and Future Scope

The most important results, findings, and suggestions for moving forward are outlined in this chapter. This study examined the hydrodynamics and thermal behaviour of five distinct microchannels that were housed in a test rig: a rectangular channel, a divergent channel, a V-shaped channel, and a meso channel. For the purpose of channel cooling, distilled water was utilised. Here, ANSYS Fluent12.0 was used to simulate a computational fluid dynamics (CFD) model in steady-state. The flow behaviour of the microchannels was observed to be affected by the Reynolds number and the Peclet number in both instances. The following inferences are made from the microchannel behaviour analysis. The calculated and analytical values of the heat transfer coefficient and temperature were very close to one another.

In both laminar and turbulent flow conditions, distilled water was found to be an effective heat transfer medium in the channel. As the Reynolds number decreased, the temperature gradient from the intake to the output grew. Even at the extremely low Peclet number, the temperature distribution was determined to be independent of radial position. As the Reynolds number rises, the pressure drop also rises. Because Peclet no is larger in a circular microchannel, the wall temperature changes very little as the Reynolds number increases. The results of the microchannel investigation allow us to draw the following conclusions: The experimental results can be predicted using the values of the computational variables such as temperature fluctuations, pressure drop, and friction factor. A higher coolant temperature results in a higher heat transfer coefficient. The microchannel entry achieves a higher heat transfer coefficient. In all microchannels, the heat transfer coefficient drops as one moves from the entrance to the exit region, but in divergent microchannels, where the circumstances are fully formed, the coefficient remains constant. In a rectangular microchannel, wall temperature rises as one moves from the entrance to the exit. The system's hydrodynamic and thermal behaviour can be accurately depicted by pressure and temperature contours.

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