Performance and optimization analysis for micro canal using analysis of variance

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ABSTRACT

This study aimed to improve heat transfer in a rectangular canal using winglets. The internal surface attachments (wings) were made of the same material as the microcanal. Geometric parameters such as height, thickness, and pitch of the wing were considered. To optimize the geometric parameters, an L9 orthogonal design of the experimental array was used. The two-dimensional geometric analysis of the fluid flow and heat transfer was performed using Ansys Fluent. A grid-dependent investigation test was conducted to ensure uncertainty within the domain cells. The output response of the numerical simulation was optimized using the sound-to-noise ratio. An analysis of variance (ANOVA) was performed to predict the percentage contributions of each factor. The operational parameter performance of the inlet velocity was analyzed based on the optimized geometry of the microcanal. The optimized values of the winglet geometry were 5 mm in height, 7.5 mm in thickness, and 15 mm in pitch. ANOVA indicated that the different parameters and their interactions contributed to the results, with 54.01% of the contribution coming from winglet thickness and a combined contribution of 27.5% from winglet height and thickness being considered significant. The results indicated that the performance of the internal surface attachment improved the heat transfer rate.

Keywords: Analysis of Variance; Fluid Dynamics; Heat transfer; Microcanal, Surface.

INTRODUCTION

As global populations continue to grow and economies develop, waste generation in every industrial sector has also increased. Improper disposal of waste can result in numerous problems, emphasizing the need for immediate action and efficient solutions.

Microcanals play a major role in electronic cooling in all electronic industries. Nowadays, machinery is so compact that the generation of heat is greater, and heat removal techniques are more challenging when the size of the machine is small. Compact heat exchangers transfer significant amounts of heat per unit volume and exhibit a high heat transfer coefficient [Fiebig M. et al., 1995]. To overcome this problem, researchers have been interested in several microcanal heat transmission enrichment systems. Different wing geometries and placements were analyzed, and the operational parameter, inlet velocity, was varied to predict the performance of the channel. The results demonstrated that the mounting configuration played a significant role in the improvement of heat transfer (Wang Q. et al., 2007). Another geometric approach used a finned oval channel element along with a delta winglet pair. It has been previously established that this geometry improves heat transfer (Chen Y et al., 2000;Tang L.H. et al. 2016). The impact of wire nets and S-shaped inserts on the performance of microchannels was studied. Although the wire net exhibited excellent heat transfer performance, the S-shaped insert reduced the pressure loss. This approach of using inserts also lowers the critical value of the Reynolds number (Jojomon Joseph et al., 2020).

The heat transfer rate in a wavy cavity was investigated by fitting a single horizontal fin to a hot wall. Parameters such as fin length and location have a considerable influence on the flow and other thermal characteristics, such as heat transfer. At a dimensionless fin length of 0.75, the maximum effectiveness was obtained. The equations were solved using the Galerkin weighted residual finite element method. In comparison to the square cavity, the wavy cavity produced more effective results in terms of heat transfer and fluid flow (Md. Fayz-Al-Asad et al., 2020). Microchannels of different geometrical forms, such as angular, curved, and wavy, were employed, and their heat exchange capabilities were compared with those of a straight channel. Both experimental and numerical (Fluent) experiments were performed. Significant deviations were observed between the laboratory and numerical results because nonlinear influences were not considered in the numerical models. In comparison with the low performance of straight channels, high friction factor of angular channels (owing to multiple sharp turns), and insignificant heat exchange enhancement of curved channels (owing to long, gentle turns), a wavy channel with excellent performance is recommended for electronic units as heat sinks or heat exchangers (Samuel D. Marshall et al., 2017).

A numerical investigation was performed on a low-Reynolds-number flow in a rectangular winglet pair. The flow increases the heat transfer significantly; however, it induces the pressure loss penalty (He Y.-L. et al., 2016, Dezan D.J. et al., 2013; Delač et al., 2016). A comparative study was conducted on the delta and inclined projected winglet pairs. The heat transfer enhancement achieved was 3.2% more for the inclined projected winglet pairs than for the delta winglets (Oneissi M. et al., 2018). The flat plate rectangular wings were considered as vortex generators to enhance the heat transfer rate. The canal with rectangular wings increased the heat transfer by approximately 58.3 and 26.2% compared to the triangular and trapezoidal wings, respectively (Tang L.H. et al., 2016, Khoshvaght-Aliabadi et al., 2015). Surface cooling is vital in an industrial application and it can be achieved by optimizing the shape variables through which the rate of heat transfer can be increased to the maximum (Kashyap et al., 2010). To improve heat transfer, various geometric parameters are involved, and the numerically simulated results of multi-objective optimization techniques, such as artificial neural networks and genetic algorithms, are examined simultaneously (Abdollahi A. et al., 2015). The China–Russia crude oil pipeline is one of the main causes of global warming, and essential support for the design of pipelines with the required thermal insulation thickness has been proposed (Lin Ding. et al., 2020). The role of air conditioners in global warming and ozone depletion was considered in this study, and an alternative refrigerant to replace R22 was proposed. An engineering equation solver was implemented, and further experimental tests and simulations were conducted, resulting in an increased effectiveness of the proposed refrigerant (Sorour Alotaibi. et al., 2021).

A liquid metal (galinstan, an alloy comprising gallium, indium, and tin) was used as the working medium to analyze the heat-transfer rate in the mini-channel. The performance of the liquid metal was observed to be better than that of water and nanofluid. Analysis of the results indicated that channel geometry, such as channel width, channel height, and flow velocity, significantly influenced flow resistance. Channels with deep and narrow geometries produced higher heat transfer than shallow and wide channels, with galinstan as the cooling fluid. The channel geometry was optimized (Adeel Muhammad et al. 2020). The optimization of the winglets of the flat-fin-based compact exchanger was analyzed and optimized using surface response methodology and direct optimization techniques (Salviano et al., 2015). A vortex generator fin-and-tube heat exchanger was optimized using the Taguchi method. Taguchi optimization techniques such as analysis of variance (ANOVA) are statistical approaches and are among the simplest and most effective methods in the robust parametric optimization technique. In total, eight factors were analyzed with an L18 orthogonal array, and it was observed that six factors significantly influenced the performance of the heat exchanger (Zeng M. et al., 2010). Several geometric Taguchi optimization methods have been applied to heat exchangers to achieve the maximum heat transfer and minimize the pressure decrease in the exchanger design (Hsieh CT. et al., 2012; Turgut E.G. et al., 2013; Tang L.-H. et al., 2016; Kotcioglu et al., 2012; Aslam Bhutta et al., 2012). Weld metal SS202 was used to optimize the input process variables that affect the output responses in the Tungsten inert gas fusion welding process, which were optimized using the Taguchi-based design method; the results were analyzed using ANOVA. (Neeraj Sharma et al., 2020; Johnson Rotimi oluremi; M.H Shwehdi et al., 2015).

METHODOLOGY

The methodology implemented in the analysis of heat transfer enhancement is shown in the flowchart below.

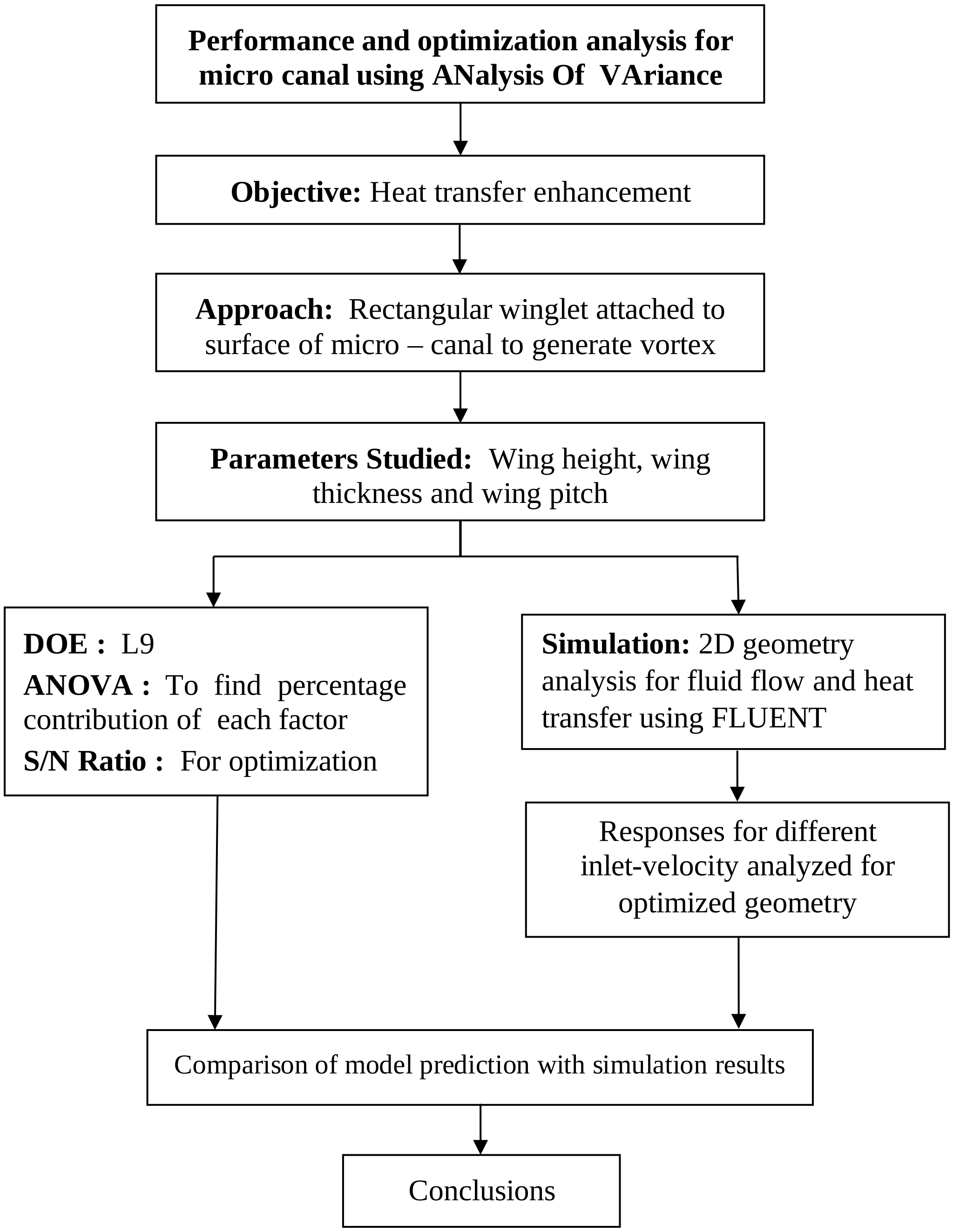


Figure. 1. Flow chart of Work Methodology

Reference channel

Copper was used as the reference channel material. Initially, using a plain copper circular canal, the experiment was conducted from a lower to a higher range of Reynolds numbers. The Reynolds number for a circular geometry was determined in a previous study [Khoshvaght-Aliabadi et al., 2015] as follows:

$$Re = \frac{u_{in} D_h \rho}{\mu}$$

$$D_h = \frac{4\, L\, A_c}{A_t},$$

where u_{in} denotes the inlet velocity in m/s, D_h is the hydraulic diameter in meters, ρ is the density of the fluid, and μ is the dynamic viscosity of the fluid. The terms L, Ac, and At denote the channel length (m), cross-sectional area (m^2), and total surface area (m^2), respectively. The properties considered were the average surface and fluid outlet temperatures. In an internal flow, the convection heat transfer coefficient is defined in terms of the Nusselt number as follows:

$$Nu = \frac{hD_h}{k},$$

where Nu denotes the Nusselt number, which is a nondimensional number with no units, h is the convection heat transfer coefficient in W/m2-K, k is the thermal conductivity of the material in W/m-K, and D_h is the length parameter of the channel. The values of the theoretical predictions are shown in Figure 1.

Physical model

Two-dimensional (2D) geometry was used in this study for flow and thermal analyses. The factors considered for 2D flow analyses were height, thickness, and pitch of the wing. The geometric parameters of these channels are listed in Table 1 [Khoshvaght-Aliabadi et al., 2015].

Table 1. Geometric parameters and levels.

Parameters		Levels		
		1	2	3
Wing height (mm)	A	2.5	5	7.5
wing thickness (mm)	B	2.5	5	7.5
Wings pitch (mm)	C	15	20	25

The Taguchi design of experiments (DOE) is the most popular and simple method for planning experiments and optimizing output responses. In this study, a Taguchi DOE was adopted to plan the experimental parametric level combinations. A Taguchi L9 orthogonal array was used for the experiments. The experimental plan and L9 orthogonal array are listed in Table 2.

Table 2. Experimental plan and L9 orthogonal array.

Experiment No	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Numerical Scheme

A finite-volume solver was used to solve the mass, momentum, energy, dissipation rate, turbulence energy, and continuity equations. A steady-state pressure-based solver was used in the study. Various turbulence models such as standard k-ε, RNG k-ε, SST k-ε, and k-ω were used to perform similar types of experiments. Among them, standard k-ε model exhibited good agreement with the experimental results [Aslam Bhutta M.M. et al., 2012]. Hence the standard k-ω turbulence model was adopted in this study. For pressure-velocity coupling, a simple scheme was applied. A constant wall temperature was assumed as the boundary condition in this study. The upstream boundary was a constant and uniform inlet velocity with an inlet temperature of 300 K. The outlet condition was atmospheric, and 0 Pa was assumed. A turbulence intensity of 10% was used in this study [Hsieh C.-T. et al., 2012]. The convergence criteria for momentum, continuity, k, and epsilon was fixed at 10^{-4}, whereas the convergence criteria for energy was fixed at 10^{-7}.

Grid dependent investigation and validation

Grid-dependent investigations are important in grid-based numerical simulations to predict the most appropriate solution. The model was designed and a mesh of good quality was synthesized. Figure 2 shows the grid-dependence investigation and validation of several cells at the outlet temperature. The number of cells within the domain varied from 1726 to 25255, among which the two finest cells, 19371 and 25255, predicted similar results with a difference of 0.56%. This result was almost equal to the theoretical predictions. To consider the computational time, the number of cells was assumed to be approximately 20000.

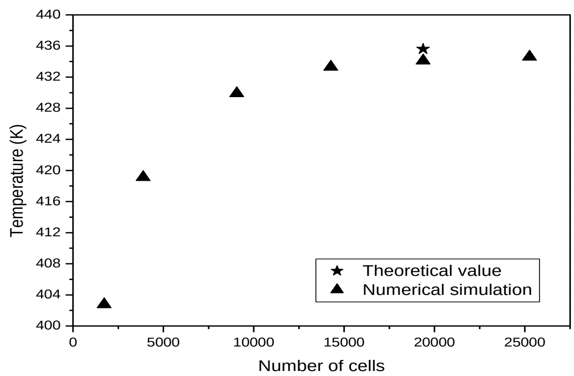


Figure. 2. Investigation and validation of grid dependence.

RESULTS AND DISCUSSIONS

Several simulations of the extended surfaces were performed after validating the results with theoretical predictions and grid-dependent studies. The output response of the temperature is listed in Table 3 along with the corresponding sound-to-noise (S/N) ratios.

Table 3. S/N ratio and temperature response of each experiment.

Experiment No.	A	B	C	Temperature (K)	S/N ratio
1	1	1	1	386.131	51.73469
2	1	2	2	372.198	51.41548
3	1	3	3	405.437	52.15847
4	2	1	2	381.345	51.62636
5	2	2	3	378.834	51.56898
6	2	3	1	431.717	52.70398
7	3	1	3	364.753	51.23998
8	3	2	1	368.374	51.32578
9	3	3	2	407.503	52.20262

Figure 3 shows the plot of the main effects of the S/N ratio for the selected condition, where a larger value is considered better, indicating maximum heat transfer from the solid surface to the water. For maximum heat transfer, the optimum geometric values of the height, thickness, and pitch of the wing were 5, 7.5, and 2.5 mm, respectively.

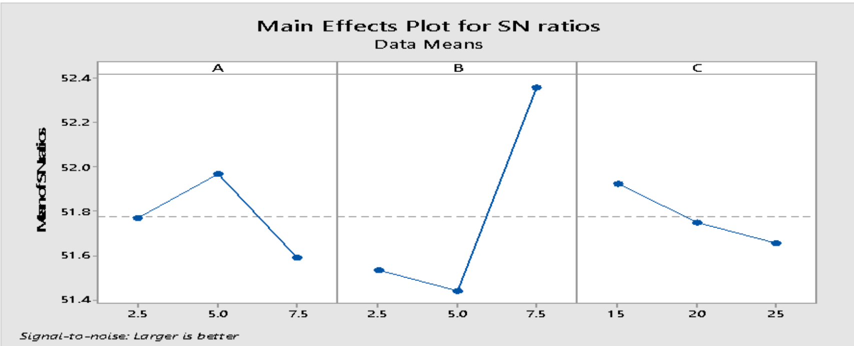


Figure. 3. Main effects of the S/N ratio.

Table 4 lists the responses of the S/N ratios under large heat transfer conditions. For the maximum heat transfer, based on the temperature response in the experiments, factors B (wing thickness), A (wing height), and C (wing patch) were ranked in the order of 1, 2, and 3, respectively.

Table 4. S/N ratios (larger is better) responses.

Level	A	B	C
1	51.77	51.53	51.92
2	51.97	51.44	51.75
3	51.59	52.36	51.66
Delta	0.38	0.92	0.27
Rank	2	1	3

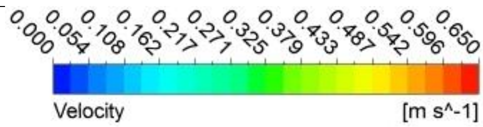
A regression model was used to determine the maximum optimal output response temperature. The R2 value of the regression equation was 98.67% and the simulation results are explained in detail. The regression equation was expressed as follows:

$$TEMP = 486.0 + 11.41\,A - 26.83\,B - 7.936\,C - 2.117\,A*A + 3.0122\,B*B + 0.1130\,C*C + 0.2027\,A*B + 0.3603\,A*C$$

Table 5 lists the ANOVA predictions, which assist in determining the percentage contribution of each factor. Factor B (wing thickness) contributed the most significantly to maximizing heat transfer, which accounted for 54.01% of the total contribution and had the highest impact among all factors. The second individual factor with the second highest contribution was factor C (wing pitch), which contributed 5.91% of the total contribution. Factor A contributed a relatively low and insignificant 2.29% to maximizing heat transfer. The combined effect of factors A and B (wing height and wing thickness) was 27.15%, whereas factors A and C (wing height and wing pitch) contributed 8.98%. All other factor combinations were insignificant.

Table 5. ANOVA predictions.

Source	DF	Seq SS	Adj SS	Adj MS	Contribution
A	1	89.21	50.33	50.332	2.29%
B	1	2106.68	227.52	227.519	54.01%
C	1	230.62	36.06	36.061	5.91%
A*B	1	1059.13	646.49	646.487	27.15%
A*C	1	350.21	350.21	350.207	8.98%
Error	3	64.8	44.82	44.813	1.66%
Total	8	3900.65			100.00%

Velocity (m/s)	

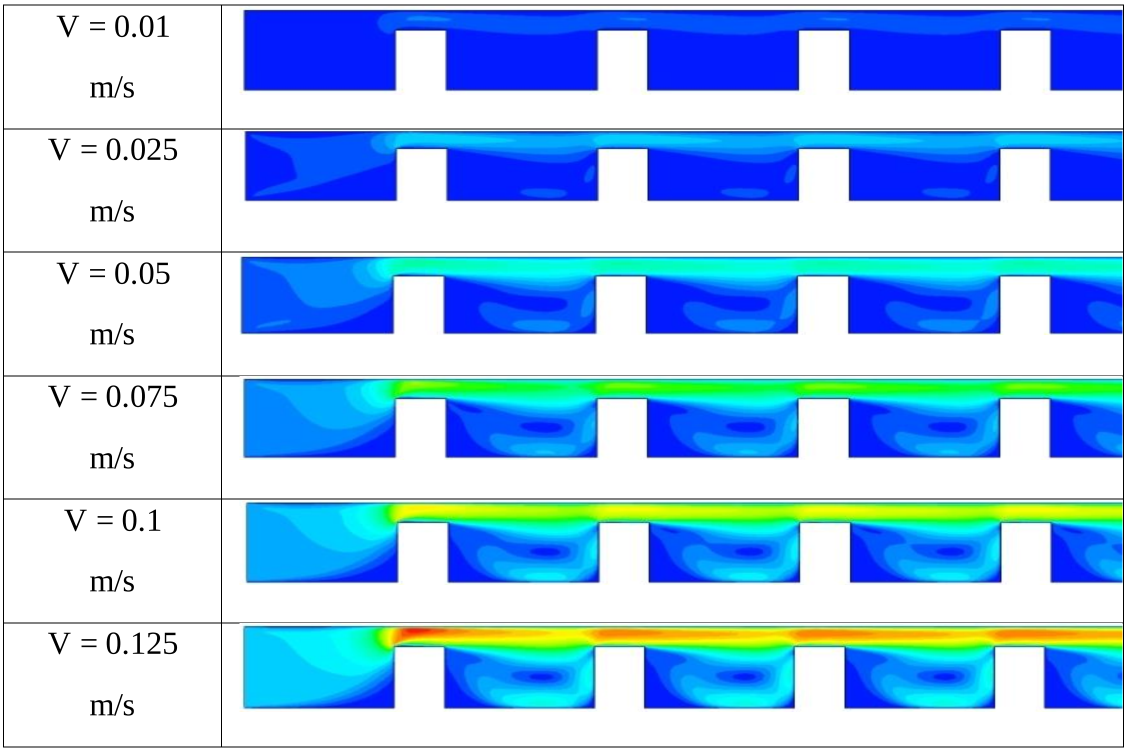


Figure. 4. Velocity contour of varying input velocities.

The velocity contours of the optimized geometric design for various velocity inputs are shown in Figure 4. Under low inlet velocity conditions, the flow through the channel in all regions was observed at a low velocity of 0.054 m/s. When the velocity increased, the direct flow path (where there is no flow restriction) exhibited the maximum velocities, and in the restricted region of the optimized space (wing pitch), the velocity of the fluid increased at high inlet velocities. This flow arrangement created a vortex in the field, which could absorb more heat from the surface. It was also demonstrated that the velocity induced by the geometry replaced that of the fresh fluid between them.

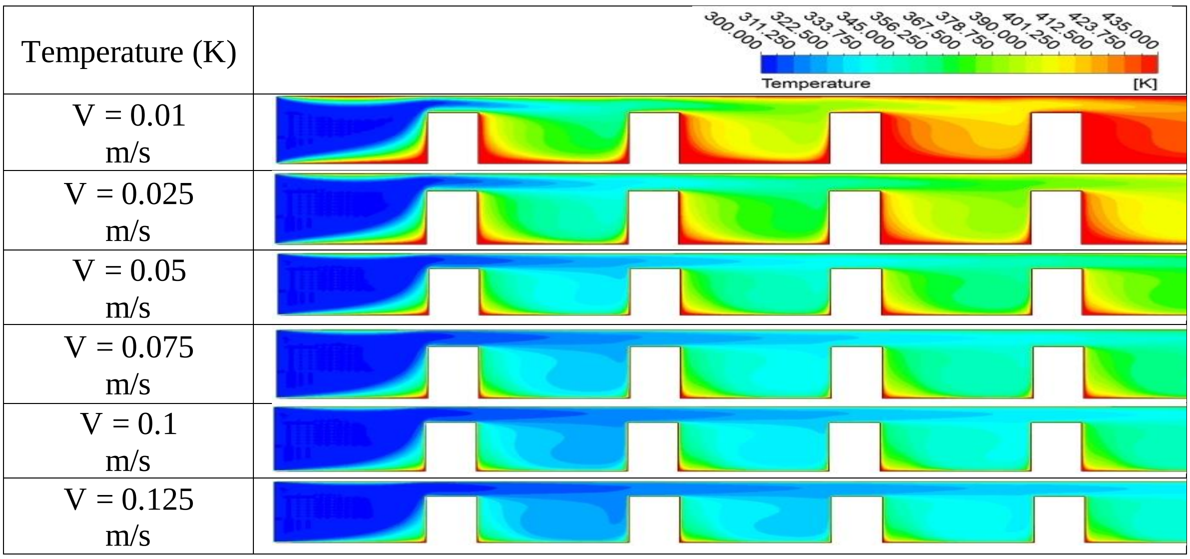


Figure. 5. Temperature contour of varying input velocities.

Figure 5 shows the temperature contours of the optimized geometric design for various velocity inputs. At a low velocity, the outlet fluid temperature was at its maximum, whereas at a high velocity, the outlet temperature was at its minimum. The high-mass flow through the canal at a high velocity replaced the stagnant fluid with fresh fluid and this is the reason why the fluid at a high-velocity outlet had a low temperature. However, this high mass flow through the channel can result in a reduction in heat transfer efficiency.

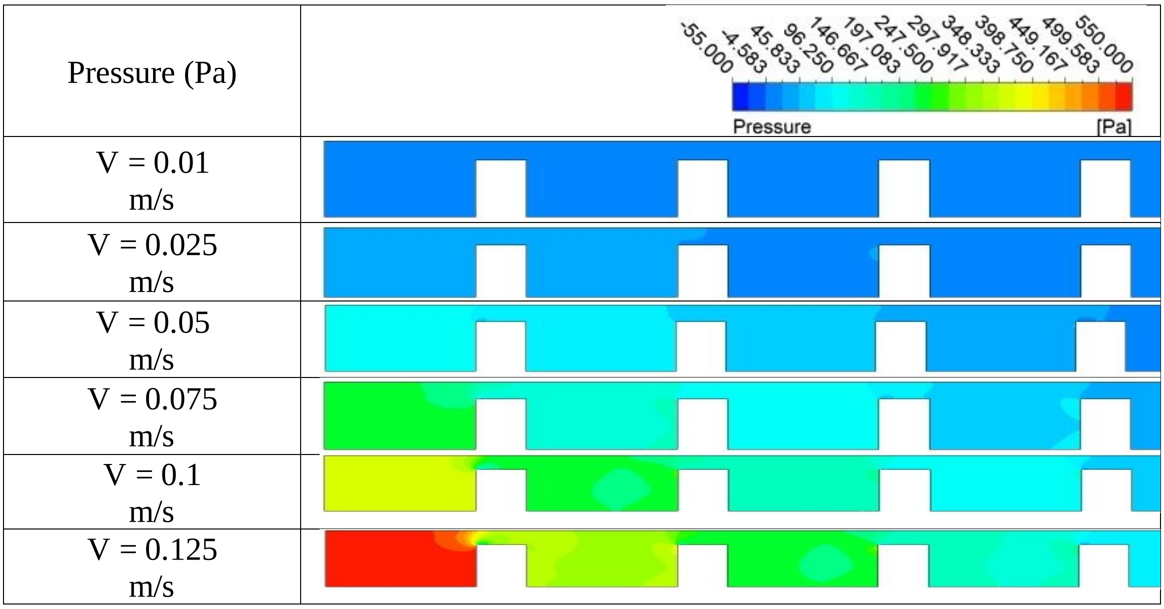


Figure 6. Pressure contour of varying input velocities.

The pressure contours of the optimized geometric design for various velocity inputs are shown in Figure 6. When the inlet velocity increased, the pressure developed from the input to the outlet also increased. This was caused by the restriction of the flow section by the surface-attached wings, which drastically reduced the flow field. This restriction increased the pressure on the inlet side. Although the pressure drop must be reduced for efficient pumping power utilization, when the heat transfer is increased, there may be a loss in pressure.

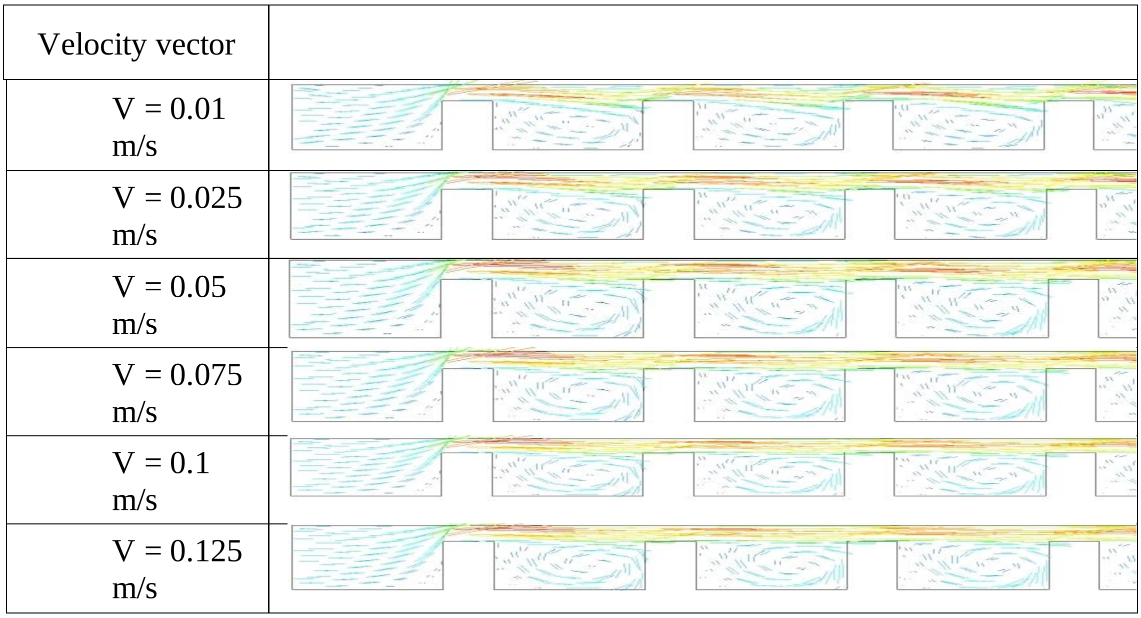


Figure 7. Vector plot of varying input velocities.

Table 6. Comparison of the predicted and simulated optimal results.

	Temperature increase (K)
Prediction	439.086
Simulated	431.717

Comparison of the prediction and simulated optimal results is listed in Table 6. The difference in the temperature response was 7.36%.

A vector plot of the optimized geometric design for various velocity inputs is shown in Figure 7. At lower velocities, the vortex formation between the rectangular wings exhibited a lower strength, as indicated by the wide horizontal axis of the vector circularity vortex. Simultaneously, when the velocity increased, the vector and vortex circularity exhibited greater strength. Therefore, the circularity of the flow field can increase the convective heat transfer rate.

CONCLUSION

The following conclusions were drawn based on the analysis of the performance and optimization results of the microcanals using ANOVA samples:

i. A rectangular winglet was designed, and its geometry was optimized with respect to the height, thickness, and pitch of the wing.

ii. The optimization values of the winglet parameters were 5, 7.5, and 15 mm for the height, thickness, and pitch of the wing, respectively.

iii. An ANOVA test was performed to determine the contribution of each factor to the enhancement of heat transfer.

iv. Parameter B, wing thickness, exhibited the highest contribution (54.01%), whereas the combined effect of factors A and B contributed 27.15% to enhancement of heat transfer.

v. The optimized geometry of the wing arrangements was investigated at various inlet velocities.

vi. The pressure drop increased at high velocities. Under similar conditions, the strength of the vortex was high, and the velocity was high at the outlet at a low temperature.

FURTHER SCOPE OF FUTURE WORK

Advanced research should focus on improving the efficiency of heat transfer in microcanals, and analyzing optimization results using ANOVA with different sizes of canal sections to further improve performance.

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