Journal of Applied Fluid Mechanics, Vol. 18, No. 10, pp. 2610-2626, 2025.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
https://doi.org/10.47176/jafm.18.10.3105

Numerical Study and Multi Objective Optimization of Coffee Husk Oil and Methyl Alcohol in Mini Channel Pin Fins with Varying Thickness

S. Das[1] and N. Gnanasekaran[1,2†]

[1] *Department of Mechanical Engineering, National Institute of Technology, Karnataka, Surathkal, Mangalore 575025, India*
[2] *Department of Mechanical Engineering, Indian Institute of Technology Tirupati, Andhra Pradesh 517619, India*

†*Corresponding Author Email:* gnanasekaran@iittp.ac.in

ABSTRACT

The purpose of this paper is to study how coffee husk oil and methyl alcohol flow and transfer heat in mini channel pin fins of different thicknesses. TOPSIS method is used to find the best configuration based on different weightages assigned for the Nusselt number and pumping power for multiple objectives. The present research work also determines the most effective configuration of mini-channel with varying pin-fin thickness in order to improve the thermo-hydraulic characteristics in compact mini-channels. Coffee husk oil and methyl alcohol are used as feedstock in a continuous flow mini-channel reactor to produce biodiesel fuel. Numerical simulations are conducted to evaluate the pressure drop, Nusselt number, temperature distribution, and pumping power for varying Reynolds number. Considering the conjugate heat transfer problem, the parameters involved are the enhancement factor, friction factor, and thermo-hydraulic performance parameter. The Reynolds number ranges from 100 to 600 for coffee husk oil and 100 to 660 for methyl alcohol. TOPSIS is applied to each case based on the numerical simulations to determine the optimal results. Upon evaluating the performance score using TOPSIS for all the scenarios, it is evident that the mini-channel with a pin thickness of 2.3 mm outperforms other mini-channel pin fin designs in most cases, for both coffee husk oil and methyl alcohol.

Article History

Received September 13, 2025
Revised May 14, 2025
Accepted May 30, 2025
Available online August 5, 2025

Keywords:

Biodiesel
Chemical reactor
Coffee husk oil
Eddies
Heat transfer
Mini channel
Multi objective Optimization
Pin fins
Pressure drop
Thermo hydraulic performance
TOPSIS
Transesterification

1. INTRODUCTION

Oil, coal, and gas are being supplanted by more sustainable alternatives in developing countries as a result of increasing prices and diminishing supplies. Due to its renewable source, biodegradability, low effect, and environmentally beneficial qualities biodiesel has been increasingly popular in the last few decades. The conventional method of producing biodiesel involves transesterification of triglycerides to provide biodiesel and glycerol (Meher et al., 2006). The investigation of biodiesel production from waste oil has been motivated by the need for environmentally friendly fuels. Industrial waste oils and by-products can be utilized for biodiesel production (Hajjari et al., 2017). Biodiesel can be produced from coffee waste stems from the abundant availability of coffee by-products and has great potential as viable fuel sources that promote sustainability. Oil, husks, and coffee grinds that are no longer useful are all produced as a result of coffee processing (Pina et al., 2019). These leftovers are often thrown away, which makes them attractive choices for biodiesel feedstocks (Sime et al., 2017). Biodiesel can be synthesized through the process of transesterification using the triglycerides present in coffee husks. The utilization of coffee waste for the production of biodiesel enables the transformation of a discarded by-product while concurrently mitigating its adverse environmental impacts. Emma et al. (2022) performed a comprehensive study on biodiesel produced from coffee husk oil and showed that it can be blended with regular conventional diesel. Also, they demonstrated a production of 700ml of biodiesel from 1000ml of coffee husk oil.

Micro and mini-channel reactors have become increasingly popular because they can effectively transfer heat and mass in highly reactive chemical processes, resulting in greater yields compared to conventional reactors, thanks to their advantageous surface area-to-volume ratio (Madhawan et al., 2018). Micro-chemical reactors utilize micro/mill reactors, micromixers, and

NOMENCLATURE

A_{min}	flow surface area of mini channel	p_{out}	pressure outlet
A_{heat}	heat source area	Δp	pressure drop
A_{total}	total area	Δp_o	pressure drop of empty channel
C_p	specific heat capacity	Q_v	volume flow rate
D_h	hydraulic diameter of mini channel	Re	Reynolds number
f	friction factor	$THPP$	Thermo Hydraulic Performance Parameter
H	height of mini channel	T_f	temperature of fluid
$h_{average}$	average heat transfer coefficient	$T_{f,average}$	average temperature of fluid
k_f	thermal conductivity of fluid	T_o	temperature of Fluid at outlet
k_s	thermal conductivity of solid	$T_{s,average}$	average temperature of solid
L	length of the mini channel	v	velocity of the fluid
Nu	Nusselt Number	v_{in}	velocity inlet
Nu_o	Nusselt Number of empty channel	v_{in}	velocity outlet
Nu_{ER}	enhancement factor	W	width of mini channel
P_{min}	perimeter of channel	η	efficiency
Pu	pumping power	ρ_f	density of fluid
p_{in}	pressure inlet	μ_f	dynamic viscosity

micro-heat exchangers. Biodiesel is produced using mixers and reaction loops composed of several components when produced from miniature micro-chemical reactors (Bordbar et al., 2020). Santana et al. (2016) was able to produce biodiesel by utilizing a reaction that used sunflower oil and ethanol, with sodium hydroxide serving as a catalyst. The synthesis was carried out with the utilization of both batch reactor and micro-reactor configurations, which resulted in the production of biodiesel at rates of 44.6 percent and 95.80 percent, respectively. Verma and Ghosh (2021) constructed serpentine channel microreactors to produce biodiesel using sunflower oil and ethanol to understand the flow regimes during the reaction. Santana et al. (2015) employed T-Channels to model the process of biodiesel synthesis in microchannels including circular obstacles. The researchers assessed the effectiveness of mixing at different Reynolds values, spanning from 1 to 160, and reaction residence periods, ranging from 0.20 to 100s. The T-channel configuration including alternating circular barriers achieved a significantly high level of mixing, reaching a maximum value of 0.99. Santacesaria et al. (2012) showed that a tubular reactor, using stainless steel ribbon wool, may obtain very high conversions quickly, at a temperature of 60°C, using a methanol/oil ratio. The observed results were in line with previous findings in the literature, which showed that the performance of static mixers or microreactors is equivalent to a value of 6. Intense local micro mixing greatly speeds up the transesterification reaction rates. Moreover, the inclusion of circular fins improved the transformation of species. Costa Junior et al. (2020) developed a micro-reactor that used micro-heat exchanger tubes and pins, which achieved a biodiesel conversion rate exceeding 90%. The maximum yield achieved a value of 99.6% when the temperature was set at 51.2 °C and the duration lasted for 0.58 min. Abdulla Yusuf et al. (2022) assessed the effectiveness of various microreactors, including four T-shaped reactors, one Y-shaped reactor, and one Tesla-shaped reactor, for continuous biodiesel synthesis which showed that the transesterification process successfully converts a molar ratio of 9:1 of methanol to oil at a temperature of 60 °C. Tiwari et al. (2018) conducted a comprehensive analysis of the latest developments in microchannel reactor designs and modifications within the domains of mechanical and chemical engineering. Their research focused on examining microstructures of various shapes, such as cylindrical fins, square fins, serpentine channels, zigzag microchannels, and T-type mixers, within a continuous tube reactor.

Pin-fins are frequently employed in diverse engineering applications to augment fluid flow, heat transfer, and micro-mixing. Maji and Choubey (2020) reviewed and analyzed numerous shapes, sizes, and configurations of pin-fins and addressed the varied applications of these different types of fins. Sarafraz and Christo (2021) designed and manufactured a 3D printed pin-fin micro-reactor and conducted numerical combined experimental studies. They developed correlations for HTC and found that the presence of pin fins in the micro-channels improved the thermal performance of the micro-reactor. Zhao et al. (2016) conducted numerical studies on several micro pin-fin architectures and angular orientations which showed that the presence of pin fins or rotating pin fins can significantly improve thermal performance. There is a paucity of literature in which researchers have thoroughly examined the thermo-hydraulic characteristics of oil and alcohol in mini channels. Wang et al. (2004) tested the frictional characteristics of mini channels with lubricating oil and water as the working fluids in both circular and rectangular channels. Ismail et al. (2013) conducted studies on viscous fluids within a mini-channel heat exchanger. Experiments were conducted to evaluate the thermo-hydraulic characteristics of deionized water, 50% ethylene glycol, motor oil, and automatic transmission fluid, the findings showed that deionized water has the highest heat transfer coefficient while Engine oil exhibited the lowest heat transfer coefficient.

This introductory section takes a look at the heat transfer and fluid flow characteristics of micro channel efficient heat exchangers used in the chemical process industries. The use of microreactors in the transesterification process for biodiesel generation is also investigated. It goes on to show that waste oil is important

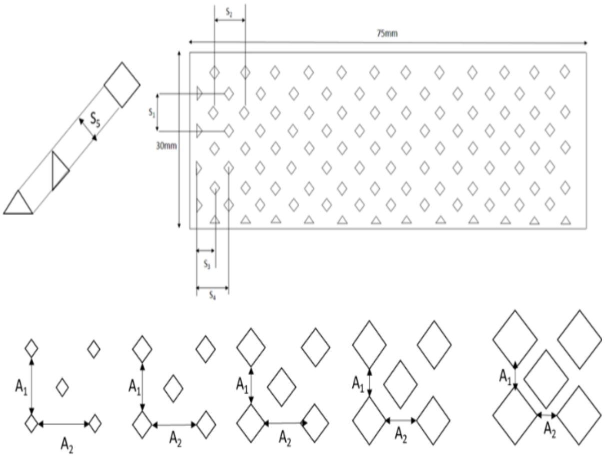


Fig. 1 Schematic of mini channel with Pin fins

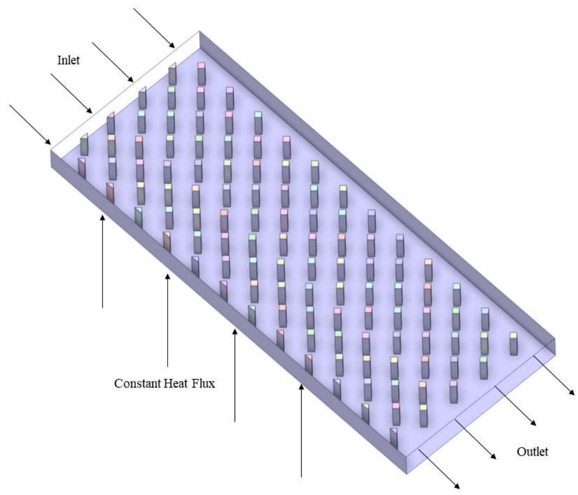


Fig. 2 Computational domain

and that there is a possibility to make biodiesel from coffee husk oil, which is a byproduct of the coffee production process. It is essential to consider the temperature of the reactor and fluid flow when constructing a mini-channel reactor with continuous flow. Due to the important nature of the reaction temperature in transesterification, it is essential to conduct fluid flow and heat transfer analyses on each reactant before the reaction. As mentioned before by modifying the flow structure and aspect ratio, pin-fin mini-channels improve fluid flow and heat transfer characteristics. They also function as static micromixers. In this study, coffee husk oil and methyl alcohol are the two fluids used in this study to examine the performance of different mini-channel pin fin arrays with different pin fin thicknesses. To find the optimal thermal and hydraulic parameters for a realistic mini-channel pin-finned reactor under various operating conditions, a numerical parametric study is carried out. Following the numerical study, the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) technique is used with various weights assigned to get more insights into the fluid flow and heat transfer characteristics of methyl alcohol and coffee husk oil in mini-channel pin fins. This study aims to develop a mini-channel pin finned biodiesel reactor by studying the thermohydraulic properties of coffee husk oil and methyl alcohol before transesterification. The results will provide extensive insights into selecting the appropriate pin fin structure and orientation in mini channel pin fin reactors along with pump selection for the two different fluids used for transesterification.

2. Numerical Methodology

2.1 Geometry Description

A mini-channel pin fin array with dimensions of 75mm×30mm×4mm is considered. This mini channel incorporates fins with a staggered arrangement of 45 ° oriented square pin-fins. This is inspired by (Pandit et al., 2014) of different fin thicknesses, as well as a version without any fins. Figure 1 shows the schematic of the pin-fin array, which has been altered by adding triangular fins at the end of the existing fins. This study involves altering the fin thickness by modifying the edge length of fins throughout the range of 1mm to 3mm. The position of the fins remains constant. Subsequently, we determine the most optimal pin fin array design by evaluating the thermohydraulic performance (THPP) by conducting a parametric analysis on the variation of fin thickness ranging from 1mm to 3mm and finally using the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) technique to get the best performance score.

Table 1 Design parameters

S_5 in mm	A_1 & A_2 in mm	S_3 in mm	S_4 in mm
1	4.59	3	6
1.4	4		
2	3.17		
2.3	2.83		
3	1.75		

The values of S_1, S_2, S_3, S_4 and S_4 and A_1 and A_2 are given in Table 1 and from geometry $S_1 = S_2 = A_1 = A_2$ and S_3 and S_4 are constant throughout, which can also be seen in Table 1. The mini-channel pin fin model comprises of 108 fins and the fin thickness or edge length S_5 is increased to find an optimum fin size for the mini-channel. The computational domain of the mini-pin fin channel is shown in Fig. 2.

The focus is now on the specific fluid flow and heat transfer properties of Coffee husk oil and Methyl Alcohol, which are the reactants involved in the transesterification reaction. This investigation necessitates the selection of a micro-reactor pump and heater prior to the reaction. The properties of Coffee Husk Oil (Hanif et al., 2019) and Methyl Alcohol (González et al., 2007) are given in Table 1. Reynolds numbers from 100 to 600 for Coffee husk oil and from 100 to 660 for Methyl alcohol is used to investigate the behavior of these two fluids. The Reynolds number is determined using the velocities of the two fluids, which range from 0.636 to 3.83 m/s for coffee husk oil and from 0.01 to 0.06 m/s for methyl alcohol. The selected velocity ranges ensure a comparable Reynolds number range of 100-600 for both fluids. Numerical simulations were performed using ANSYS FLUENT 22,

Table 2 Properties of Methyl Alcohol and Coffee husk oil

Property	Methyl alcohol	Coffee husk oil
Density (kg/m^3)	784	890
Thermal Conductivity (W/mK)	0.199	0.06
Specific Heat Capacity (J/kgK)	2546	1670
Viscosity (kg/ms)	0.0005	0.04

considering variation of fin spacing and one case without fins.

2.2 Boundary Conditions and Governing Equations

The boundary conditions for the numerical simulation are pressure exit and velocity entry. Additionally, the lower surface maintains a 10 W/cm^2 steady heat flow, and a 1 mm thick solid substrate connects the fluid and solid surfaces. Except for the surfaces specified above, all remaining surfaces are governed by adiabatic wall boundary conditions. The solid domain is composed of copper, with a density of 8850 kg/m^3, a thermal conductivity of 398 W/mK, and a specific heat capacity of 390 J/kgK. The Mini-Pin Fin Array employs Coffee husk oil and Methyl Alcohol as the liquids for studying their thermal and flow properties before transesterification. The characteristics of these liquids are presented in Table 2.

The boundary conditions for the problem are as follows:

Inlet conditions for the purpose of simulations:

$$v = v_{inlet} = \text{constant},\ T_f = T_{in} = \text{constant} \quad (1)$$

In regard to the calculation model's lateral walls:

$$\frac{\partial u}{\partial y} = \frac{\partial w}{\partial y} = v = 0,\ -k_s\frac{\partial Ts}{\partial y} = 0 \quad (2)$$

In regard to the calculation model's base walls:

$$\frac{\partial u}{\partial y} = \frac{\partial w}{\partial y} = v = 0,\ -k_s\frac{\partial Ts}{\partial y} = 0 \quad (3)$$

In regard to the other walls of the calculation model:

$$u = v = w = 0,\quad \frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0 \quad (4)$$

The velocity components are represented by u, v, and w, and the coordinates are given by x, y, and z. Two variables, q (heat flux across the bottom wall) and k_s (thermal conductivity), represent these ideas, respectively. The Reynolds number range examined in this study is 100 to 600 for coffee husk oil and 100 to 660 for methyl alcohol. Thus, the laminar flow calculation model is utilized. Furthermore, the convergence thresholds for the continuity criteria and energy criteria in ANSYS FLUENT are 10^{-4} and 10^{-8}, respectively. The fluid dynamics and heat transfer in a mini channel pin-fin reactor utilized for transesterification present a challenging three-dimensional coupled conjugate heat transfer problem that includes chemical reactions.

In order to streamline the calculation procedure, several assumptions are made as a result of the intricate nature of theproblem:

1. The impact of volumetric forces, surface tension, and radiative heat transfer is not considered.

2. The fluid is characterized as incompressible, exhibiting a consistent and smooth flow.

3. It is assumed that the viscosity and temperature of the fluid stay consistent throughout the phenomenon of fluid flow.

4. There is no vapourization of methyl alcohol and coffee husk oil taking place.

The governing equations of the computational domain are as follows :

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (5)$$

X-momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \quad (6)$$

Y-momentum equation:

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \quad (7)$$

Z-momentum equation:

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \quad (8)$$

Energy equation of the fluid:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (9)$$

Energy equation of the solid:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (10)$$

In this study the hydraulic diameter and Reynolds number are defined as:

$$D_h = \frac{4A_{\min}}{P_{\min}} \quad (11)$$

Where P_{min} and A_{min} are the minimum perimeter and flow area of the channel, respectively.

$$Re = \frac{v\rho_f D_h}{\mu_f} \quad (12)$$

Where v_{flow}, ρ_f, and μ_f are the free stream velocity, density and, dynamic viscosity.

The average heat transfer coefficient ($h_{average}$), friction factor (f), THPP (η), enhancement factor (Nu_{ER}), average Nusselt number (Nu_{avg}) and, pumping power (Pu) are defined as:

$$h_{average} = \frac{q_w A_{\text{heat}}}{A_{\text{total}}\left(T_{S,\text{ average}} - T_{f,\text{ average}}\right)} \quad (13)$$

$$Nu_{average} = \frac{h_{\text{average}} D_h}{k_f} \quad (14)$$

$$f = \frac{2\Delta p D_h}{\rho_f v^2 L} \quad (15)$$

$$\eta = \frac{Nu/Nu_0}{(\Delta P/\Delta P_0)^{1/3}} \quad (16)$$

$$Nu_{ER} = \frac{Nu}{Nu_0} \quad (17)$$

$$Pu = \Delta p Q_v \quad (18)$$

q_w, A_{heat}, A_{total}, $T_{s,average}$, $T_{f,average}$, and k_f represent the heat transfer of the surface of the heat source (which is equal to 10 W/cm^2), heat source area, total area, average temperature of surface, average temperature of fluid, and thermal conductivity of fluid, respectively. f represents the friction factor. Δp is the pressure drop across the mini-channel considered in the present research work

Nu_{ER} represents the enhancement factor. It is the ratio of the Nusselt number of the specific pin fin channel to the Nusselt number of the empty channel with no fins. η represents the THPP which is the Thermal Hydraulic Performance parameter. It is the ratio of the Enhancement factor to the ratio of the friction factor of the modified flow conditions to the friction factor of the empty channel with no fins raised to the power of 1/3. The Thermo Hydraulic Performance Parameter evaluates the combined effect of heat transfer enhancement and the associated pressure drop or pumping power penalty in a heat transfer system. When a heat transfer enhancement is introduced in pin fins it often increases heat transfer but also increases the pressure drop in the system, which requires more pumping power.

- If the thermo-hydraulic performance parameter is greater than 1, it signifies that the use of pin fins improves the thermo-hydraulic performance compared to an empty channel.
- If the thermo-hydraulic performance parameter is lower than 1, it signifies that the use of pin fins degrades the thermo-hydraulic performance compared to an empty channel.

2.3 Grid Independent Study

The different mini channel Pin fin arrays with edge lengths of 1mm, 1.4mm, 2mm, 2.3mm and 3mm are meshed using ANSYS FLUENT Mesher with Polyhedral cells with each having a minimum cell size of 0.2mm and maximum of 0.5mm cells. The grid independence study of mini channel with 1mm fin thickness is shown using coffee husk oil at *Re* 600 for cells having 2542365, 3756821, 4756823, 5489652 and 6032656. The pressure drop is calculated for the mini channel with 1mm fin thickness at *Re* 600 and shown in Table 3. As is evident, the computed grid number of 5489652 cells show a deviation of less than 0.1% for a cell dimension of 0.2mm. So the grid size with 5489652 cells is chosen for the numerical study and a cell dimension of 0.2mm is used throughout the numerical study for meshing the geometry. Table 3 shows the grid independent study performed for the case of mini channel with 1mm edge pin fins for *Re* 600 with coffee husk oil.

2.4 Numerical Method Validation

To validate the numerical method used in this present study, the D-MPF (Diamond micro-pin fin) geometry is exactly modelled from the studies of (Xia et al., 2017) which are exactly similar to the 45 º oriented square pin fins used in the mini channel in this study. The pressure drop and Nusselt number are taken as the input parameters for *Re* 50-300 which is a common range of flow for this present work and the study performed by (Xia et al., 2017). Their study focused on using de-ionized water in place of methyl alcohol and coffee husk oil which are the fluids used in this study. According to the principle of dynamic similarity, the mini-channel 45 º oriented square pin fins is comparable to the micro-channel heat sink used by (Xia et al., 2017). The results suggested a deviation of less than 2% from the original study, which can be seen in Fig. 3 and Fig. 4.

Table 3 Grid Independent study of 1mm edge pin Fins at Re 600 for Coffee husk oil

Number of Cells	Pressure drop in Pa	Relative error %
2542365	99263.48	0.98
3756821	99642	0.58
4756823	99978.45	0.245
5489652	100123.776	0.1
6032656	100224	-

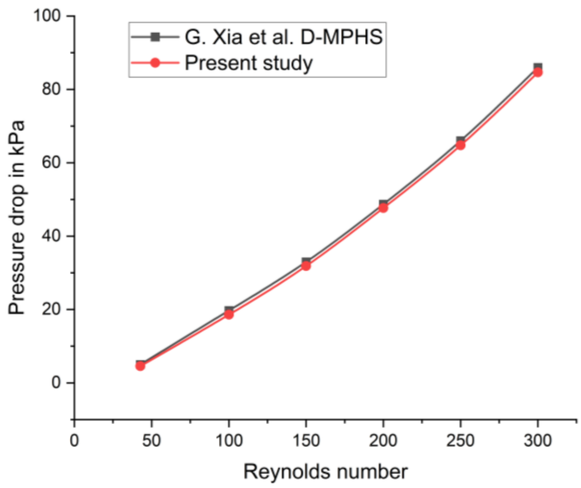


Fig. 3 Pressure drop validation

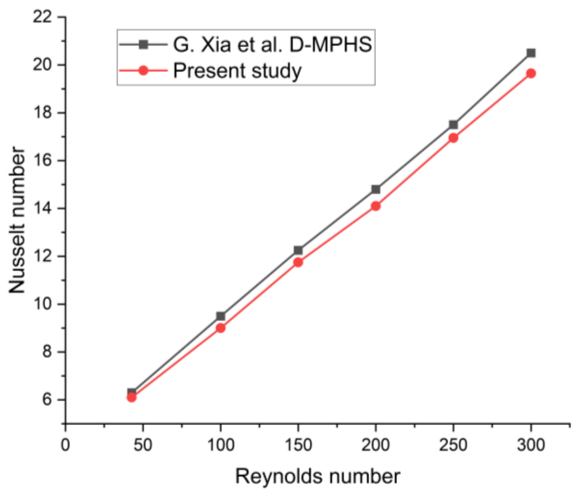


Fig. 4 Nusselt number validation

2.5 Performance Score Calculation Using TOPSIS

After computing the thermo-hydraulic characteristics of the mini channel pins fins, the Technique for order performance by similarity to ideal solution (TOPSIS) method is utilized to calculate the performance score for each and every case for both coffee husk oil and methyl alcohol for every geometry.

The method is formulated as follows:

1. There are n goals and m possible solutions laid out in a matrix. The value of the i^{th} option for the j^{th} objective is represented by each element a_{ij}, where i ranges from 1 to m and j ranges from 1 to n. This matrix can also be written as $(a_{ij})_{m\times n}$.

2. It follows that we construct a normalized matrix with the following formula: for all i = 1, 2,.., m and all j = 1, 2,.., n where

$$an_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}} \tag{19}$$

3. A weighted normalized decision matrix is then generated by assigning relative importance to each objective parameter chosen for the problem. It is important to determine the weights such that $\sum_{j=1}^{n} w_j = 1$. Following these steps, a weighted normalized matrix is formulated which is calculated as follows:

$$awn_{ij} = an_{ij}.w_j \tag{20}$$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$.

4. We find the optimal positive solution (I_j^+) and the worst negative solution (I_j^-) in relation to the goals. This allows us to determine the positive ideal solutions (d_i^+) and negative ideal solutions (d_i^-), which can be represented as follows:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(awn_{ij} - I_j^+\right)^2} \tag{21}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(awn_{ij} - I_j^-\right)^2} \tag{21}$$

The next step is to determine how close the answer is to the ideal positive solution by:

$$D_i^+ = \frac{d_i^-}{d_i^- + d_i^+} \tag{22}$$

5. Finally the performance score is assigned based on values of D_i^+ and is ranked accordingly. In this present study the results obtained from the numerical parametric study is used to formulate the matrix containing data of Nusselt number ($Nu_{average}$) and Pumping power (Pu). In this specific problem the $Nu_{average}$ and Pu is chosen as the objectives with maximizing $Nu_{average}$ and minimizing Pu for the mini-channel with pin-fins with variation of thickness. Previously this method has successfully been applied to pin fins with Phase Change materials to optimize melting time and solidification time based on pin fin positioning and height (Nedumaran et al., 2024). While (Jadhav et al., 2022) computed performance scores by TOPSIS in optimization study flow through metal foams for forced convection heat transfer applications. This method facilitates the allocation of varying weights to the capacity to optimize the preferred result and the capacity to mitigate the unfavorable result. Consequently, it facilitates a more profound comprehension of the effects of many variable conditions. The methodology for this work is illustrated in Fig. 5 shown below.

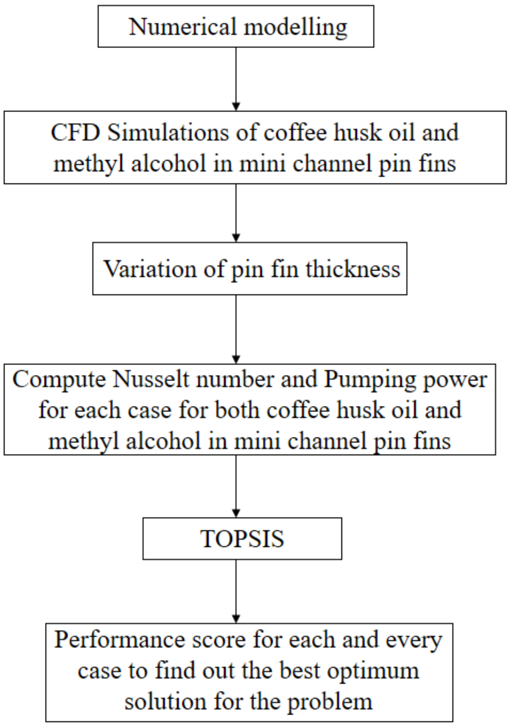


Fig. 5 Methodology of the present work

3. Results and Discussion

3.1 Variation of Hydraulic Characteristics

The hydraulic properties of coffee husk oil and methyl alcohol are depicted in Figs 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15. These figures give an illustration of the flow characteristics. Figures 6 and 7 illustrate the differences in pressure drop that occur as a result of the combination of coffee husk oil and methyl alcohol. As the velocity of the fluid increases, there is a proportional rise in pressure drop for both methyl alcohol and coffee husk oil. Both coffee husk oil and methyl alcohol show very similar trends in pressure drop and friction factor. Coffee husk oil shows a very high pressure drop compared to methyl alcohol which can be attributed to it being more viscous and having more density than methyl alcohol. However, there is very little difference in the friction factor plots shown in Fig. 8 and Fig. 9 as friction is dimensionless and is independent of fluid properties. It can also be seen that there is an inverse correlation between friction factor f and Reynolds number Re. Figure 10 and Fig.11 shows the pumping power requirement of coffee husk oil and methyl alcohol over the various mini channel pin fin configurations. It is evident that as pressure drop increases with increase in fluid velocity it leads to an increased demand for pumping power and as it can be seen from Fig.6, 7, 10 and 11, Coffee husk oil has higher pumping power requirement compared to methyl alcohol.

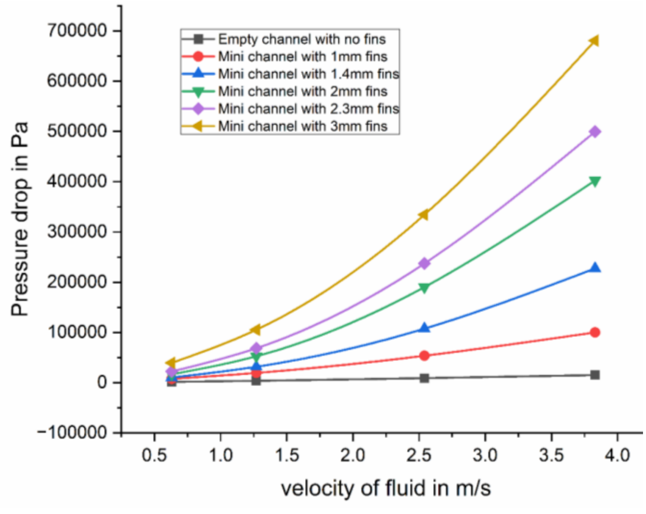


Fig. 6 Variation of Pressure drop with change in fluid velocity for Coffee husk oil

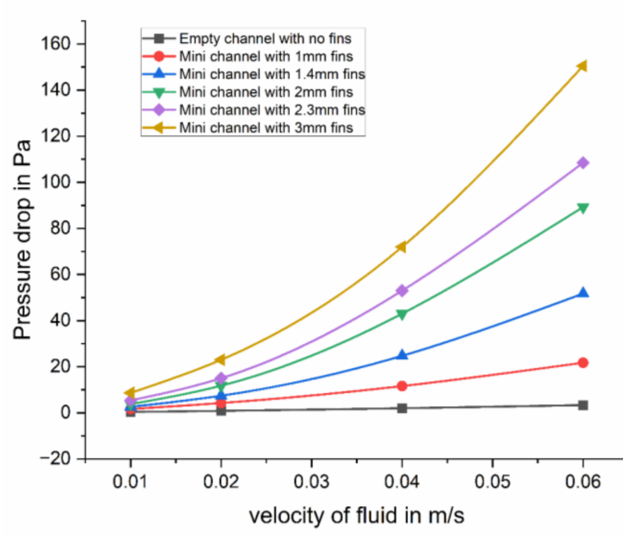


Fig. 7 Variation of Pressure drop with change in fluid velocity for Methyl Alcohol

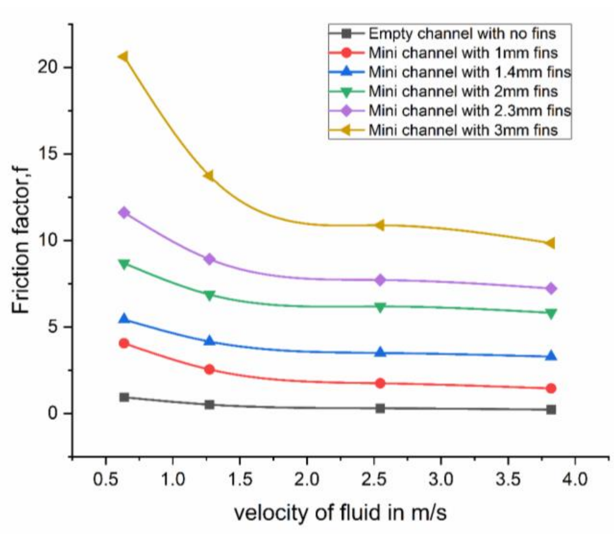


Fig. 8 Variation of Friction factor with change in fluid velocity for Coffee husk oil

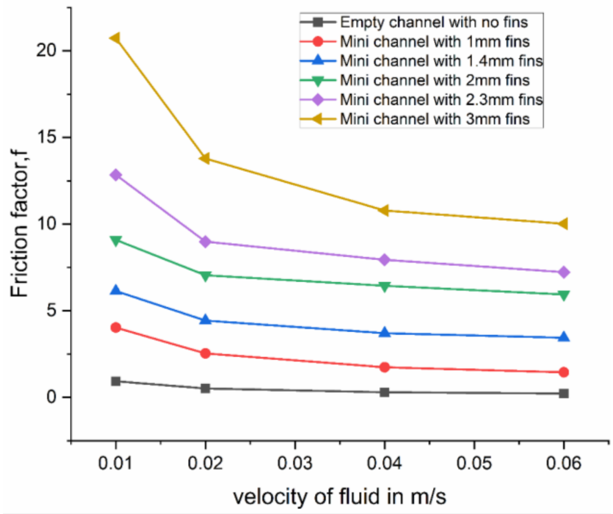


Fig. 9 Variation of Friction factor with change in fluid velocity for Methyl alcohol

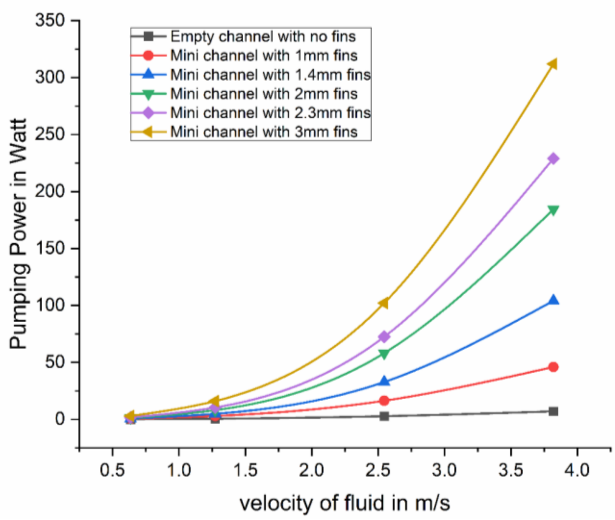


Fig. 10 Variation of Pumping Power with change in fluid velocity for Coffee husk oil

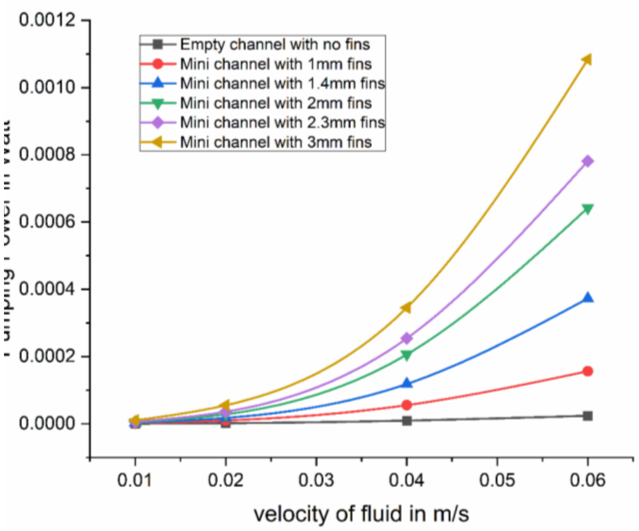


Fig. 11 Variation of Pumping Power with change in fluid velocity for Methyl alcohol

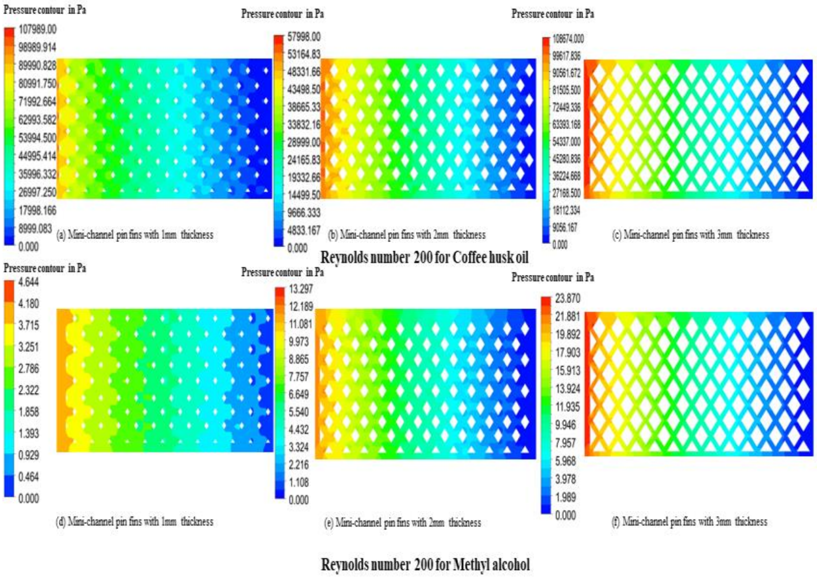


Fig. 12 Pressure contour at *Re* 200

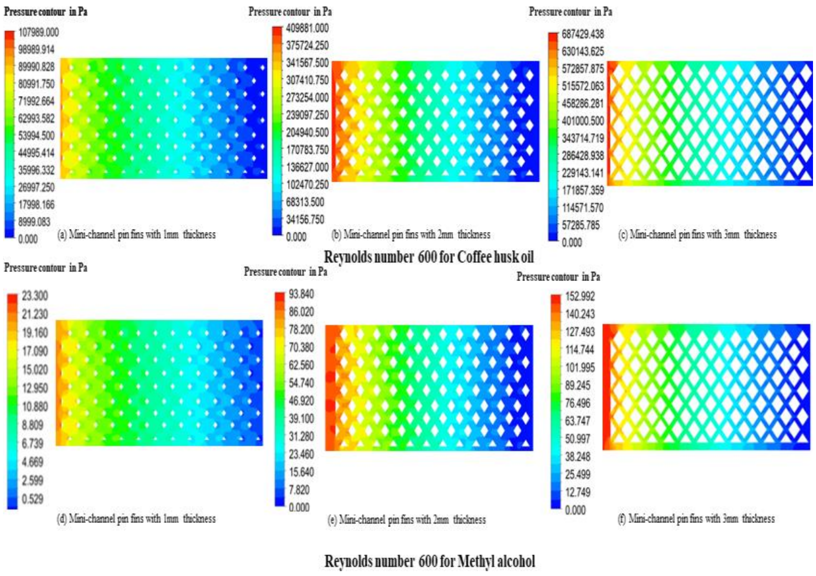


Fig. 13 Pressure contour at *Re* 600

The coffee husk oil exhibited a peak pressure drop of 680,749.2241 Pa at a velocity of 3.83 m/s, corresponding to a Reynolds number of 600 in the mini channel with a 3 mm pin fin thickness. In contrast, methyl alcohol demonstrated a maximum pressure drop of 150.5 Pa at a velocity of 0.06 m/s, corresponding to a Reynolds number of 664 in the same mini channel configuration. This suggests that when using coffee husk oil and methyl alcohol simultaneously for a continuous tubular micro/mini reactor two separate pumping devices are required for the two fluids which are the feedstock for transesterification. These results and data can be used to determine the pump ratings when selecting oil pump for oil and micro syringe pump for methyl alcohol for a mini channel transport device as depicted in this problem.

According to this parametric study on pin fin thickness for coffee husk oil and methyl alcohol, Figs 12-15 illustrate the pressure contours and velocity contours of coffee husk oil and methyl alcohol for a Reynolds number of 200 and 600 respectively, for a pin fin thickness ranging from 1mm to 3mm. These contours apply to both the pressure and velocity of the mini-channels. There is a low-pressure recirculation zone that is generated behind fins, which leads to the production of eddies and vortices, which can be seen clearly in Figs 14 and 15. This can be observed from the various pressure and velocity contours that have been created. In addition, the streamlines and the flow recirculation zone that are located behind the pin fins are depicted in Fig. 16. These eddies and vortices are present in both coffee husk oil and methyl alcohol, and they are responsible for the localized turbulence that occurs as a result of the pin fin structures creating obstructions to the flow. Increasing the thickness of the pin fin causes the volume contained within the mini-channel to shrink, which in turn leads to a reduction in the amount of space that exists between the fins. It has been observed that increasing the thickness of the pin fins results in a reduction in the occurrence of eddy formation behind the fins. This is primarily explained by the fact that there is a limited space between the pin fins. One of the

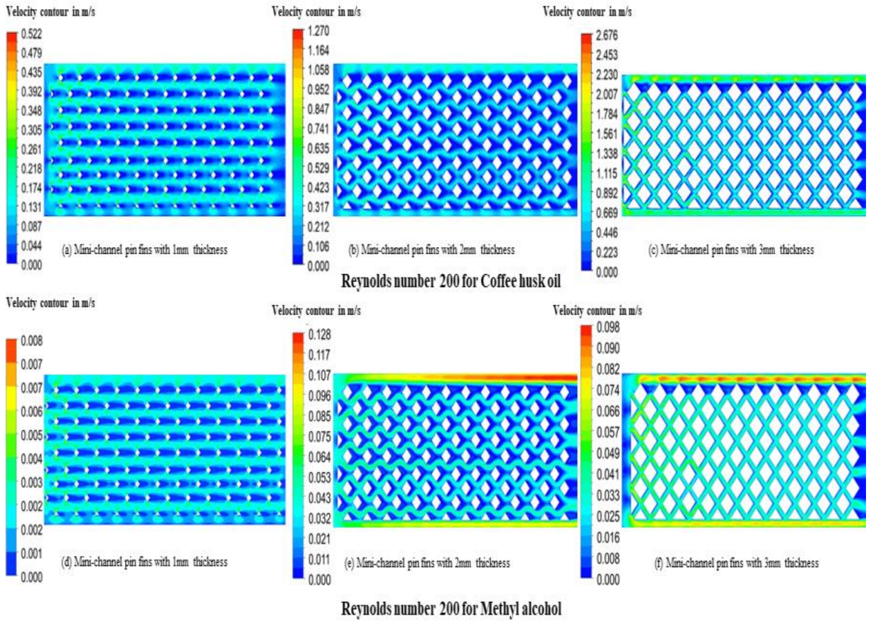


Fig. 14 Velocity contour at *Re* 200

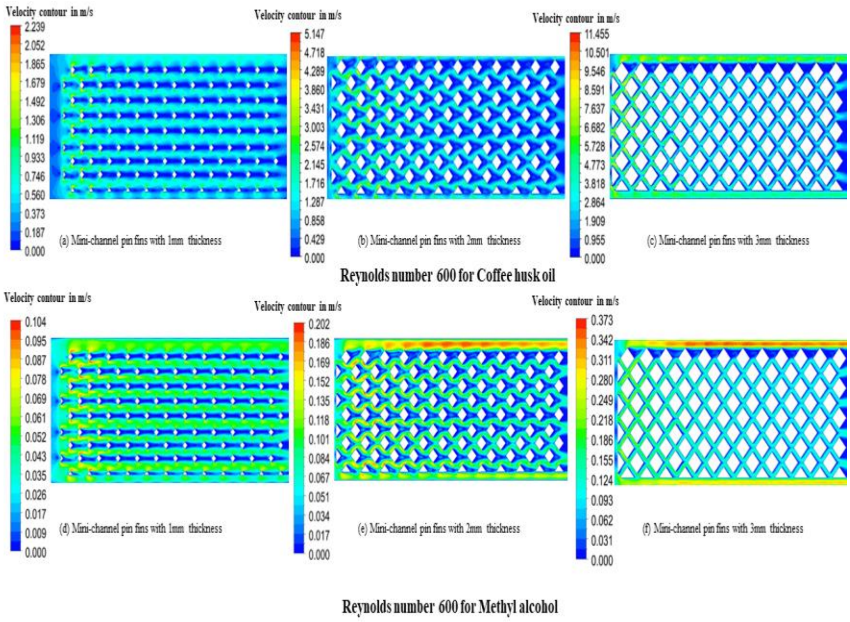


Fig. 15 Velocity contour at *Re* 600

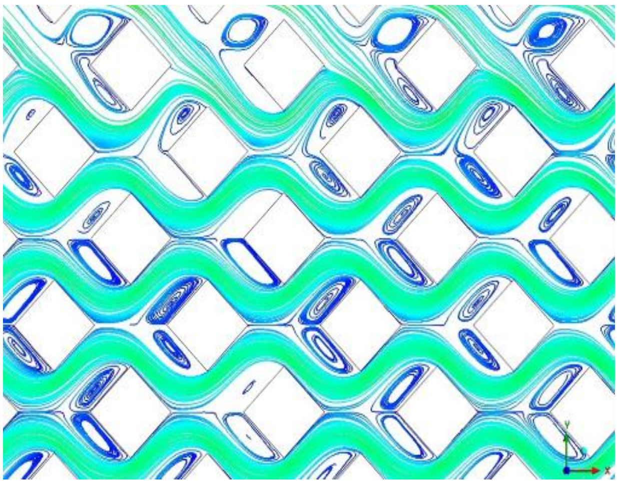


Fig. 16 Eddy formation behind fins

most significant aspects of fluid dynamics in systems with pin fins is brought to light by this observation. The production of eddies is effectively restricted when the thickness of the fins is increased because this results in a reduction in the amount of space that is available for flow between neighboring fins. It is quite probable that the disruption of the low-pressure zones behind the fins, which are generally responsible for the production of eddies, is the cause of this decrease in the formation of that phenomenon. The flow is more streamlined, which minimizes the amount of turbulence that occurs in the wake of the fins, which could ultimately lead to a flow pattern that is more predictable and uniform.

3.2 Thermal Characteristics

Figures 17-22 illustrates the thermal characteristics of coffee husk oil and methyl alcohol in the mini channel pin

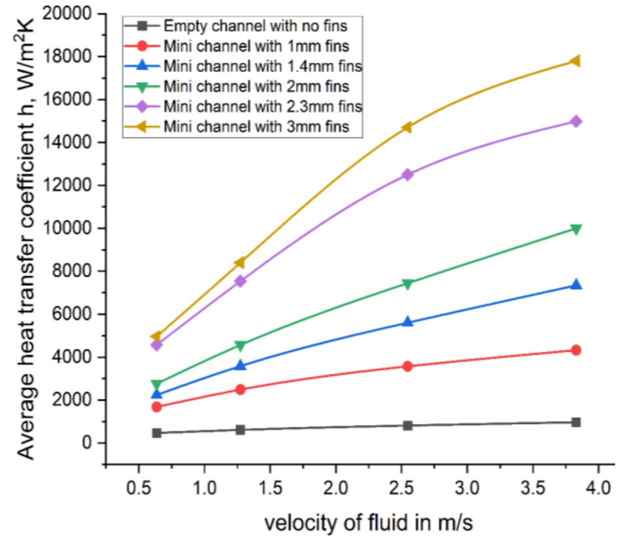


Fig. 17 Variation of Average heat transfer coefficient with fluid velocity for Coffee husk oil

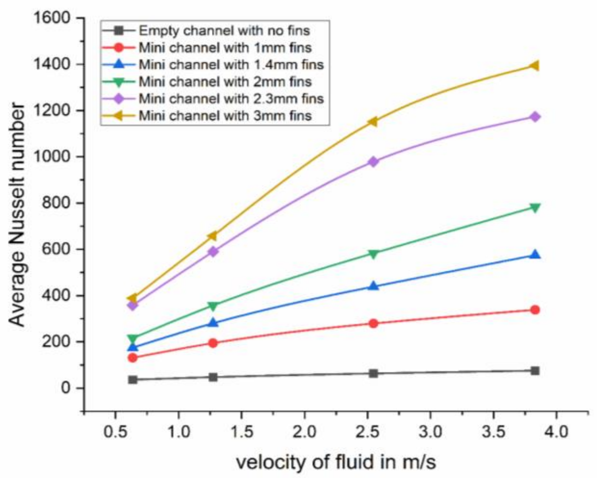


Fig. 19. Variation of Average Nusselt number with fluid velocity for Coffee husk oil

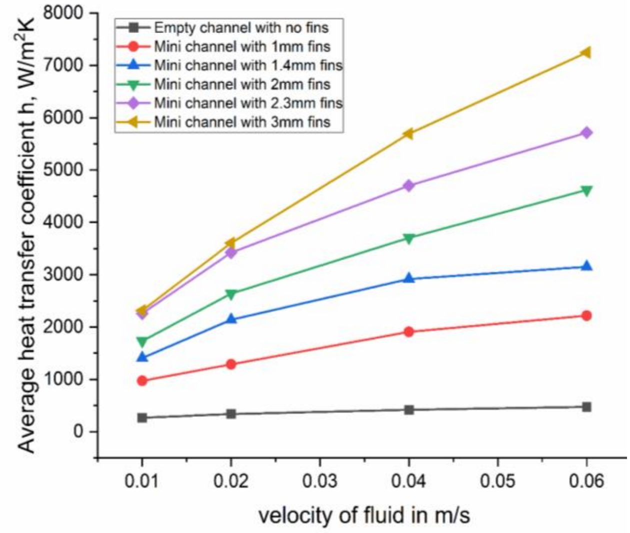


Fig. 18 Variation of Average heat transfer coefficient with fluid velocity for Methyl alcohol

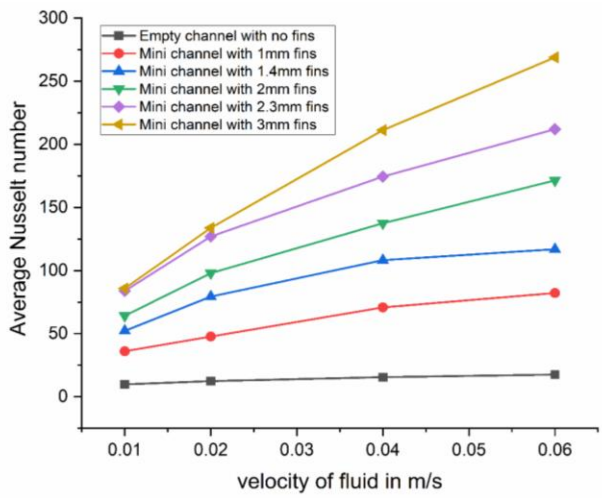


Fig. 20 Variation of Average Nusselt number with fluid velocity for Methyl alcohol

fins. Figure 17 and Fig. 18 shows the relationship of Average heat transfer coefficient and Fig. 19 and Fig. 20 shows the average Nusselt number for both coffee husk oil and methyl alcohol as a function of velocity of fluid. Figure 21 and Fig. 22 shows the temperature profile across the various mini-channel pin fin configurations for *Re* 200 and *Re* 600 for both coffee husk oil and methyl alcohol. There is a significant difference in temperature profiles for coffee husk oil and methyl alcohol in the mini channel pin fins as the highest temperature recorded in the mini-channel fins is 354 K for mini channel with cylindrical pin fins for coffee husk oil while for methyl alcohol the highest recorded temperature is 446.789 at *Re* 200. Similarly in Fig. 22 for *Re* 600 same trends has been observed as the highest temperature recorded is 335.83 K for mini channel with cylindrical pin fins for coffee husk oil while for methyl alcohol a temperature of 382.128 K is recorded which is due to the fact that heat transfer happening between the mini-channel pin fins and coffee husk oil is more compared to methyl alcohol. The average heat transfer coefficient and average Nusselt number for coffee husk oil are considerably greater than those for methyl alcohol in all configurations of the mini channels, including the whole transport phenomena. Ismail et al. (2013) reports similar trends and results for Engine Oil and reported that deionized water had the highest heat transfer rate and heat transfer coefficient. In contrast, engine oil showed the lowest heat transfer rate and heat transfer coefficient along with the highest pressure drop. The reason for this is that oil has a higher density and viscosity compared to methyl alcohol. A consequence of this is that it is able to transmit heat from the base substrate of the mini channel pin fins in an effective manner. Due to this, the base temperature is reduced, which ultimately results in an increase in the average Nusselt number originating from the solid-fluid interface region. Ultimately, this leads to a larger heat transfer coefficient that is determined from the base substrate of the mini channel pin fins as it can be seen from the physics of this conjugate heat transfer problem.

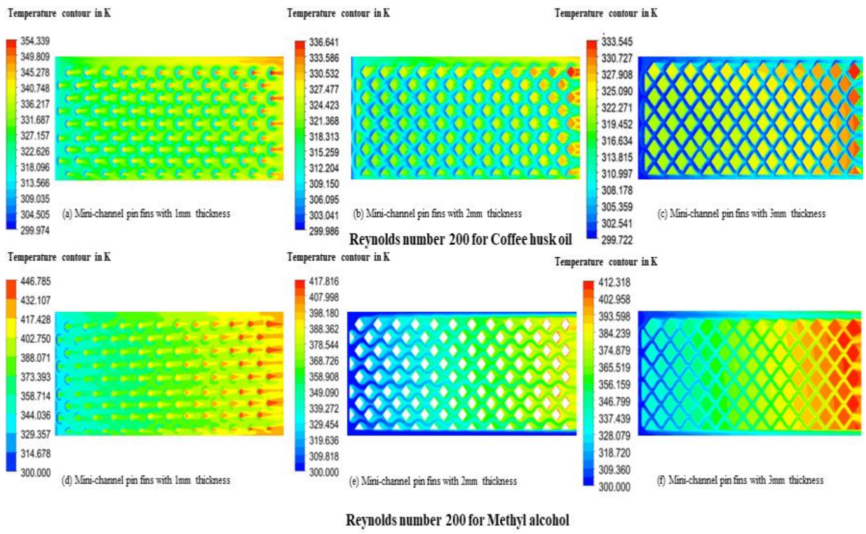


Fig. 21 Temperature Contour at *Re* 200

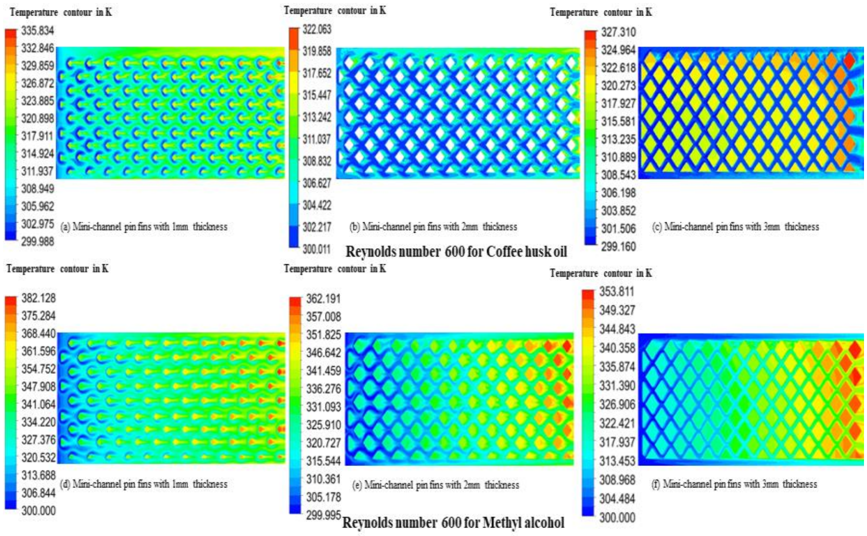


Fig. 22 Temperature Contour at *Re* 600

Furthermore, it is evident that the heat transfer rate rises as the pin fin thickness increases. Specifically, the pin fin with a thickness of 3mm exhibits the highest average heat transfer coefficient and Nusselt number. This increase in heat transmission is also accompanied by an increase in pressure drop. As heat transfer increases, there will be a corresponding rise in pressure loss.

Thicker pin fins offer an expanded surface area for heat transfer, hence improving thermal performance. A thickness of 3 mm attains the maximum average heat transfer coefficient and Nusselt number, signifying an ideal shape for enhancing heat transmission. Although thicker fins improve heat transmission, the resultant rise in pressure drop may counteract thermal performance benefits if energy consumption escalates excessively. The system's efficiency must reconcile heat transfer increase with the energy expenditure of pumping, as discussed in section 3.3.

3.3 Effect of Enhancement Factor and THPP

To assess the efficiency of the mini-channel consisting of pin fins. The Enhancement factor and Thermo-hydraulic performance parameter (THPP) are computed using equations 16 and 17, as mentioned previously. The parameters are computed for every case in the numerical analysis to analyze the thermo-hydraulic efficiency of each mini channel with varying pin fin thickness. Figure 23 and Fig. 24 depicts the Enhancement factor of coffee husk oil and methyl alcohol, while Fig. 25 and Fig. 26 display the Thermo-hydraulic performance parameter (THPP) of both Coffee husk oil and Methyl alcohol in numerical simulations done at various fluid velocities and different mini-channel pin fin thicknesses. The heat transfer enhancement factor η compares the thermal performance of a particular case with an empty channel. Fig. 23 demonstrates that the Enhancement factor of Coffee husk oil increases as the velocity of fluid increases for all mini channel configurations. However, from Fig. 24 it can be seen for methyl alcohol for mini channels with fin thickness other than 3mm the increasing curve flattens from *0.02-0.05m/s* for methyl alcohol. The mini-channel, designed 3mm thickness pin fins, exhibits the highest Thermal Hydraulic Performance Parameter (THPP). The maximum value of THPP for coffee husk oil is seen at a fluid velocity of 2.5m/s with a value of 5.5. For methyl alcohol the highest THPP is seen at 0.06m/s at Reynolds number of 664 corresponding to it, with a value of 4.25.

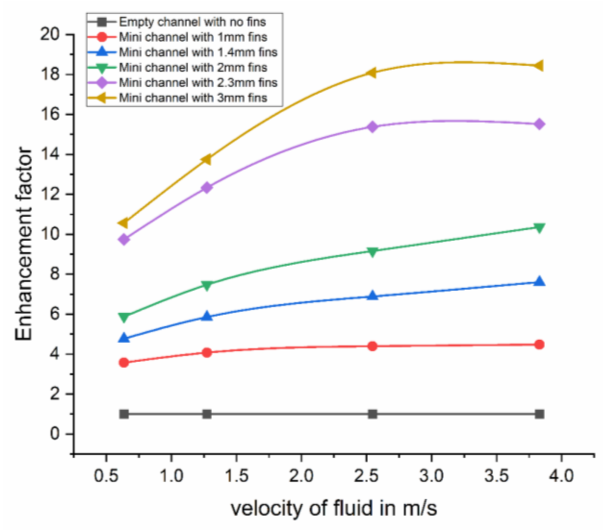


Fig. 23 Variation of Enhancement factor with fluid velocity for Coffee husk oil

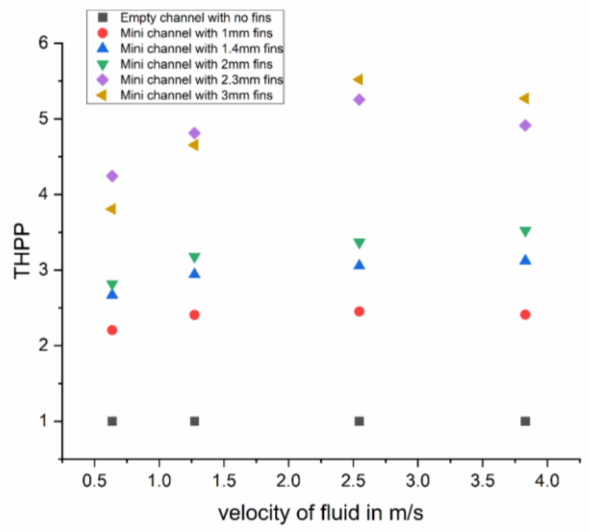


Fig. 25 Variation of THPP with fluid velocity for Coffee husk oil

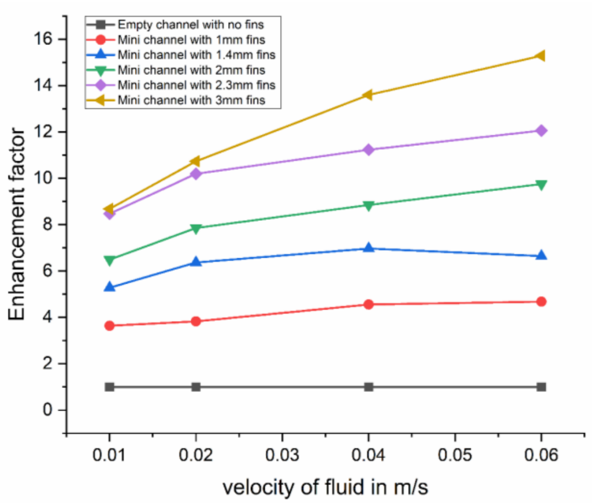


Fig. 24 Variation of Enhancement factor with fluid velocity for Methyl alcohol

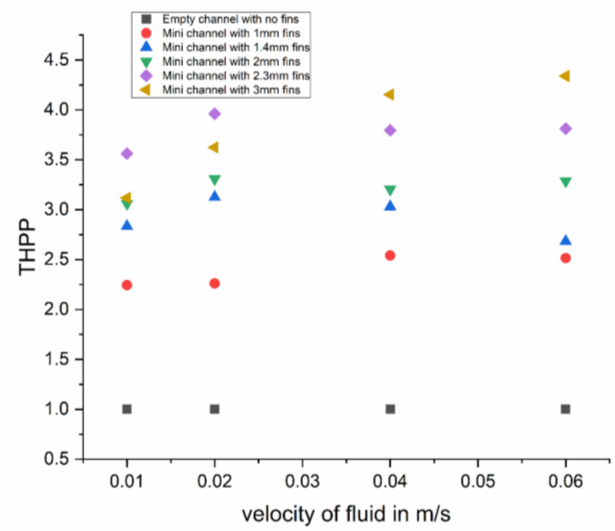


Fig. 26 Variation of THPP with fluid velocity for Methyl alcohol

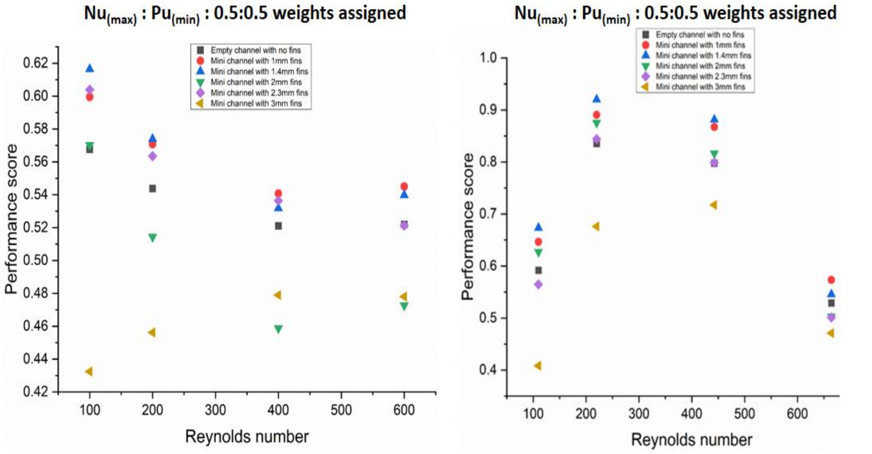
The mini channel with 2.3mm fin thickness shows the second highest THPP followed by the mini channel with 2mm, 1.4mm and 1mm fin thickness. The empty channel without pin fins shows the lowest THPP.

These results emphasize the importance of balancing heat transfer and pressure drop to optimize the thermal-hydraulic performance of mini channels. While thicker fins enhance heat transfer, they also increase the system's energy demands, making intermediate thicknesses like 2.3 mm a practical choice for many applications. In the present work, the values for enhancement factor and Thermo-hydraulic performance parameter are greater than 1 for all the considered cases except for the empty channel, indicating the improvement in the thermal and thermo-hydraulic performance of the thermal systems compared to the empty configuration.

3.4 Performance Score Optimization using TOPSIS

The objective is often to optimize heat transfer while minimizing pumping power. Regrettably, these two objectives are in direct opposition to one another. If one attempts to augment the velocity in order to enhance the heat transfer coefficient and therefore boost heat transfer, the pressure drop and pumping power will concurrently escalate. As a result, an optimization technique would generally produce numerous answers known as Pareto-optimal solutions, rather than just one solution. This means that if we attempt to enhance one aim, it will automatically lead to a deterioration in the other objective. To be more precise, there is no distinct optimal solution. One way solving this kind of multi-objective problem is by assigning different weightages or preferences to the objectives. In this specific problem the objectives are heat transfer and pumping power as mentioned earlier. So, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) can used in this problem.

Based on the numerical results obtained for mini channel pin fins with varying thickness for both Coffee husk oil and Methyl alcohol TOPSIS can be applied. The



(a)Variation of Performance score with Reynolds number for Coffee husk oil **(b)Variation of Performance score with Reynolds number for Methyl alcohol**

Fig. 27 Performance score for Criteria – I

objective here would be to maximize Nusselt number (*Nu*) and minimize Pumping power (*Pu*). So based on these two objectives we assign different weightages for Nusselt number (*Nu)* and Pumping Power (*Pu*). For this specific problem 4 weights are considered for *Nu: Pu* which are 0.5: 0.5, 0.65: 0.35, 0.75:0.25 and 1:0. For each different weightage criteria there will be different performance scores for each and every case separately for coffee husk oil and methyl alcohol. This performance score investigation based on TOPSIS method is carried for all the mini channel designs comprising of varying pin fin thickness as well as for the empty channel for all the cases. Sections 3.1, 3.2, and 3.3 utilize the fluid velocity of both coffee husk oil and methyl alcohol to analyze their thermal and hydraulic characteristics. The velocity ranges are 0.636-3.83 m/s for coffee husk oil and 0.01-0.06 m/s for methyl alcohol, corresponding to Reynolds numbers from Re 100 to Re 600 for coffee husk oil and Re 100 to Re 660 for methyl alcohol, establishing a common Reynolds number regime for this analysis. This paper uses Reynolds number (*Re*) as a benchmark to compare methyl alcohol and coffee husk oil under similar laminar flow conditions in the mini channels filled with pin fins similar to the studies conducted by (Salman, 2019) and (Basha et al., 2024) where they used Reynolds number as a benchmark to compare different nanofluids in various channel configurations. TOPSIS method is applied for a detailed comparative analysis with a Reynolds number range from 100-600 for both coffee husk oil and methyl alcohol which focuses on two objectives: the Nusselt number (Nu), which is contingent upon heat transfer, and the pumping power (Pu), which is influenced by the system's pressure drop. The ascribed weights for Nu: Pu are 0.5:0.5, 0.65:0.35, 0.75:0.25, and 1:0. Greater emphasis is placed on the Nusselt number in relation to heat transfer, as optimizing heat transfer is the primary focus in this issue, given that the pumping power demand is minimal for a mini-channel of the specified dimensions. In practical applications involving smaller mini channel heat exchangers, heat transmission is prioritized over pumping power, necessitating the use of small-sized pumps. Comparable research involving weight assignments has been conducted by (Jadhav et al., 2022) for a channel containing a metal foam heat exchanger, while (Ning et al., 2016) employed TOPSIS with weights to optimize the supply vane angle in an air conditioning system concerning energy efficiency and thermal comfort in buildings.

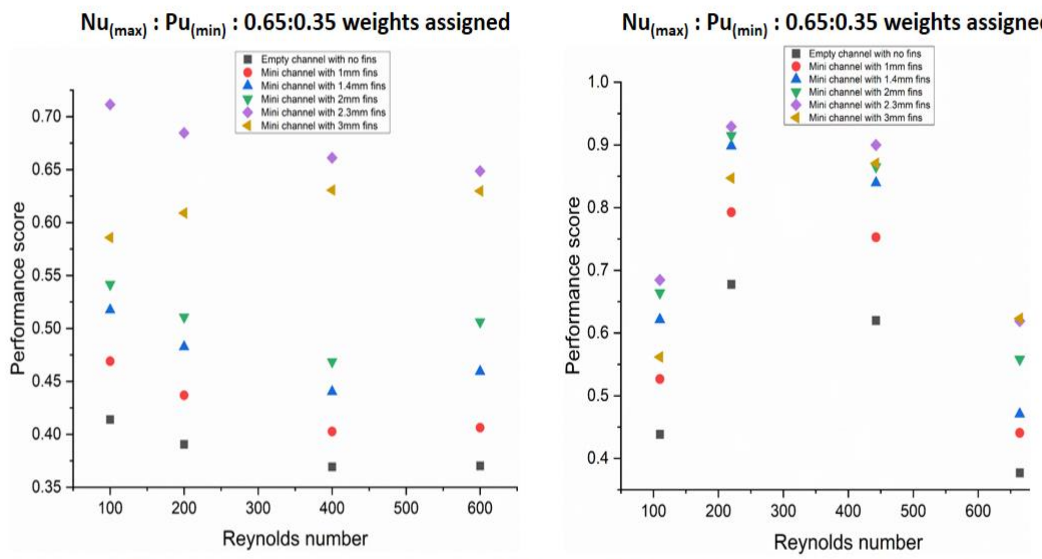
The objective of employing TOPSIS is to meticulously analyze the thermo-hydraulic characteristics of coffee husk oil and alcohol, utilizing Reynolds number as a benchmark for the two distinct fluids, with a focus on heat transfer rather than pumping power.

3.4.1 Criteria – I ($Nu_{max} : Pu_{min} = 0.5 : 0.5$)

In this condition equal weightage is given to both Nusselt number and Pumping power. The results for this condition and performance score with variation in *Re* 100 to *Re* 600 for coffee husk oil and for *Re* 100 to *Re* 660 for methyl alcohol can be seen in Fig. 27. For equal weightage given Nusselt number and Pumping power, the mini channel with 1.4mm thickness shows the highest performance score from *Re* 100 to *Re* 400 followed by 1mm thickness and 2.3mm thickness pin finned mini channels for the case of coffee husk oil. In case of methyl alcohol except for *Re* 600, mini channel with 1.4 mm pin fins shows the highest performance score followed by 1mm and 2.3mm mini channel pin fins. The mini channel with 3mm pin fin thickness shows the lowest performance score for methyl alcohol. For Coffee husk oil the mini channel with 3mm pin fin thickness has the lowest performance scores at *Re* 100, *Re* 200 but ranks second from the bottom at *Re* 400 and *Re* 600 with the mini channel configuration with 2mm thickness having the lowest performance score at *Re* 400 and *Re* 600.

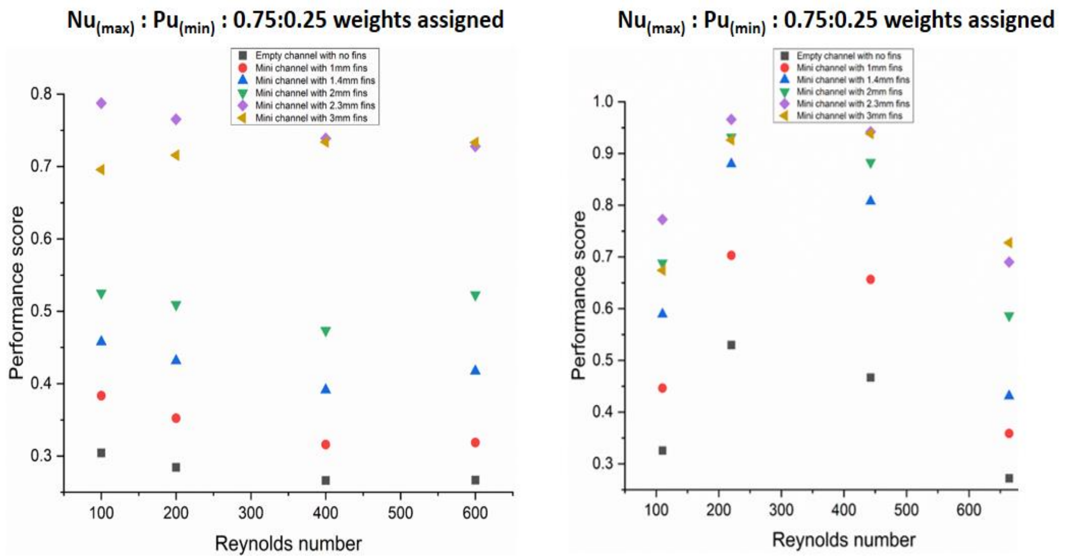
3.4.2 Criteria – II ($Nu_{max} : Pu_{min} = 0.65 : 0.35$)

In this condition slightly higher weightage is given to Nusselt number over Pumping power resulting in 65% weightage given to Nusselt number and remaining 35% to Pumping power. The results for this condition and performance score with variation in *Re* 100 to *Re* 600 for coffee husk oil and for *Re* 100 to *Re* 660 for methyl alcohol can be seen in Fig. 28. In this criterion, the mini channel with 2.3mm pin fin thickness shows the highest performance score from *Re* 100 to *Re* 600 followed by 3mm thickness, 2mm thickness,1.4mm thickness and 1



(a)Variation of Performance score with Reynolds number for Coffee husk oil **(b)Variation of Performance score with Reynolds number for Methyl alcohol**

Fig. 28 Performance score for Criteria – II



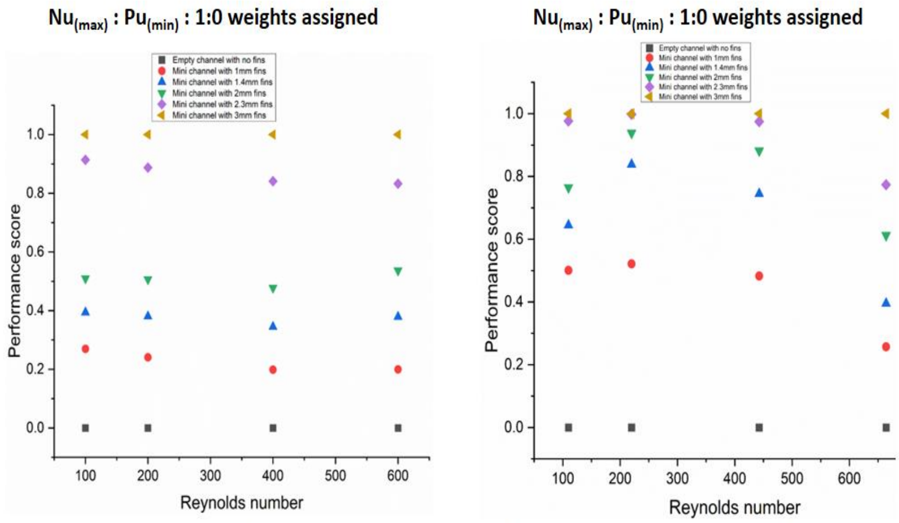
(a)Variation of Performance score with Reynolds number for Coffee husk oil **(b)Variation of Performance score with Reynolds number for Methyl alcohol**

Fig. 29 Performance score for Criteria – III

mm thickness pin finned mini channels for the case of coffee husk oil. In case of methyl alcohol also, the mini channel with 2.3 mm pin fins shows the highest performance score. However, in case of methyl alcohol in the range *Re* 100 to *Re* 500, the mini channel with 2mm pin fin thickness has the second highest performance score followed by 3mm mini channel pin fins and at *Re* 660 3mm mini channel pins has higher performance score than 2mm mini channel pin fins and achieves a performance score almost equivalent to mini channel with 2.3mm pin fins. The empty channel shows the lowest performance score for both coffee husk oil and methyl alcohol followed by the mini channel with 1mm pin fin thickness.

3.4.3 Criteria – III (Nu_{max} : Pu_{min} = 0.75 :0.25)

In this scenario, Nusselt number is assigned a much higher level of importance compared to Pumping power, with 75% weightage given to Nusselt number and the remaining 25% allocated to Pumping power. The results for these criteria and performance score with variation in *Re* 100 to *Re* 600 for coffee husk oil and for *Re* 100 to *Re* 660 for methyl alcohol can be seen in Fig. 29. In this criterion, the mini channel with 2.3mm pin fin thickness shows the highest performance score from *Re* 100 to *Re* 400 followed by 3mm thickness, 2mm thickness, 1.4mm thickness and 1mm thickness pin finned mini channels for the case of coffee husk oil. After *Re* 400 to *Re* 600 the mini channel with 3mm pin fin thickness shows the highest performance score while other pin fin mini channel configurations do not show any change in the trend. In the case of methyl alcohol also, the mini channel with 2.3 mm pin fins shows the highest performance score alcohol in the range *Re* 100 to *Re* 500, the mini channel with 2mm pin fin thickness has the second highest performance score at *Re* 100 followed by followed by 3mm mini channel pin fins. Beyond *Re* 500 3mm mini channel pins has higher



(a)Variation of Performance score with Reynolds number for Coffee husk oil (b)Variation of Performance score with Reynolds number for Methyl alcohol

Fig. 30 Performance score for Criteria – IV

performance score than 2.3mm mini channel pin fins which ranks second. 2mm mini channel pin ranks third. The empty channel shows the lowest performance score for both coffee husk oil and methyl alcohol. The mini channel with 1mm pin fin thickness and 1.4mm pin thickness ranks the second lowest and third lowest in terms of performance score as per the criteria for both coffee husk oil and methyl alcohol.

3.4.4 Criteria – IV (Nu_{max}: Pu_{min} = 1:0)

In this scenario, the Nusselt number is just considered, while the pumping power is not taken into account. The results for this condition and performance score with variation in *Re* 100 to *Re* 600 for coffee husk oil and for *Re* 100 to *Re* 660 for methyl alcohol can be seen in Fig. 30. For entire weightage given to Nusselt number, the mini channel with 3mm pin fin thickness shows the highest performance score from *Re* 100 to *Re* 600 followed by the mini channels with 2.3mm pin fin thickness, 2mm pin fin thickness, 1.4mm pin fin thickness, 1mm pin fin thickness and the empty channel for both coffee husk oil and methyl alcohol. It is very well understood by now that increasing pin fin thickness increases the heat transfer which in turn increases the Nusselt number. Also increasing pin fin thickness results in increase of pumping power and since no weightage is given for pumping power the performance scores in this condition are following a very usual trend as per general intuition for both the fluids.

4. CONCLUSIONS

The aim of this present paper is to obtain better thermal and hydraulic insights for mini channels with varying pin fin thickness using coffee husk oil and methyl alcohol as fluids prior to a chemical reaction refereed as transesterification. In order to perform the chemical process with optimal productiveness, numerical simulations for 48 cases were performed in ANSYS FLUENT 22. The mini channel with pin fins of varying thickness were developed for this study. The pin fin thickness was varied from 1mm to 3mm. This study uses coffee husk oil as an alternative to conventional edible oils and methyl alcohol as the fluids for the mini channel with pin fins. These fluids are the feed stocks for the chemical process of transesterification which is the chemical production of biodiesel. This study focuses on the thermo hydraulic characteristics of coffee husk oil and methyl alcohol in a mini channel filled with pin fins for the development of a miniature pin finned reactor for biodiesel synthesis. Prior to transesterification in mini channel pin finned reactors individual thermo hydraulic characteristics of the fluids need to be studied which is the purpose of this work. The multi-objective optimization utilized a dependable TOPSIS algorithm. The work focused on two objective functions: decreasing pumping power and maximizing the Nusselt number. Four criteria were chosen based on the assigned weightage in relation to the objective function. Performance ratings were plotted for different pin fin thicknesses in the micro channel, based on each criterion. After the investigation was finished, the following observations were made.

- The pressure drop is lowest for the empty mini channel, however it is significantly higher when employing 3mm pin fins. Furthermore, there is a substantial disparity in the pumping power between the two fluids. Coffee husk oil necessitates approximately 300 W at a Reynolds number of 600, but methyl alcohol only requires a micro-syringe pump with less than 1 W. Therefore, it is essential to choose distinct pump ratings in a certain sequence to effectively pump both fluids in the mini-channel pin fin array system.
- The heat transfer characteristics of coffee husk oil are superior to those of Methyl alcohol, resulting in a larger heat transfer coefficient and Nusselt number variation with Reynolds number. It is due to Coffee husk oil having higher density and higher viscosity over methyl alcohol for which it can absorb more heat from the base substrate of the mini channel resulting

higher heat transfer for a comparable Reynolds number range.

- Based on the multi objective optimization study performed on Nusselt number and pumping power for criteria - I 1.4mm pin thickness has the highest performance score followed by 2.3mm fin thickness and 1mm fin thickness. In criteria - II and criteria III the mini channel with 2.3mm thickness has the highest performance score and for the final criteria IV 3mm pin fin thickness shows the highest with 2.3mm pin thickness showing the second best. From an average of all the performance scores of all cases for both the fluids the 2.3mm pin fin thickness has the highest average performance score and is the most optimum design for this study.

This study possesses certain limitations. The flow is presumed to be laminar throughout all cases and mini-channel designs; nevertheless, increased pin fin thickness results in greater eddies and turbulence, as illustrated in Fig. 16. To accurately numerically describe the transport phenomena, a transition turbulence model can be used which has been not been used in this kind of a problem validated with experimental data. Also, this problem assumes that the viscosity and temperature remain constant, which might not hold in real-life scenarios involving biodiesel reactors that use compact mini-channels as examined in this present study. An experimental study using optical methods like Particle Image Velocimetry (PIV) can address these constraints, yielding more precise results and facilitating the comparison of numerical outcomes to assess their accuracy without relying on the aforementioned assumptions.

Finally, it has been assumed that no vaporization of alcohol occurs throughout the investigation. In actual biodiesel reactors utilizing compact mini channel devices, vaporization of alcohol invariably occurs during the process, given that the boiling point of alcohol is 64.7 ºC. In practical applications, maintaining a constant temperature boundary condition is unfeasible; thus, with a heat flux supply of 10 W/cm^2, it is impossible to sustain a temperature below the boiling point of alcohol, resulting in the vaporization of a portion of methyl alcohol, which is not addressed in this study. To address this shortcoming, the CFD Multiphase model should be employed and tested against experimental data to achieve a more precise solution. These deficiencies may be further examined subsequent to this investigation.

Conflict of Interest

The authors of this paper have independently completed all aspects of the work, including design, calculation, and writing. This manuscript has not been previously submitted to any journal. The authors affirm that there is no conflict of interest between the findings of this study and any previously published investigations.

Authors Contribution

Soham Das: Investigation, Software, Validation, Writing – original draft, Visualization. **N Gnanasekaran:** Conceptualization, Methodology, Validation, Supervision, Writing – review & editing.

References

Abdulla Yusuf, H., Hossain, S. M. Z., Aloraibi, S., Alzaabi, N. J., Alfayhani, M. A., & Almedfaie, H. J. (2022). Fabrication of novel microreactors in-house and their performance analysis via continuous production of biodiesel. *Chemical Engineering and Processing - Process Intensification*, *172*(January). https://doi.org/10.1016/j.cep.2022.108792

Basha, S. M. M., Ahammed, M. E., Perumal, D. A., & Yadav, A. K. (2024). A Computational approach on mitigation of hotspots in a microprocessor by employing CNT nanofluid in bifurcated microchannel. *Arabian Journal for Science and Engineering*, *49*(2), 2199–2215. https://doi.org/10.1007/s13369-023-08168-y

Bordbar, A., Kheirandish, S., Taassob, A., Kamali, R., & Ebrahimi, A. (2020). High-viscosity liquid mixing in a slug-flow micromixer: a numerical study. *Journal of Flow Chemistry*, *10*(2), 449–459. https://doi.org/10.1007/s41981-020-00085-7

Costa Junior, J. M., Naveira-Cotta, C. P., De Moraes, D. B., Inforçatti Neto, P., Maia, I. A., Da Silva, J. V. L., Alves, H., Tiwari, M. K., & De Souza, C. G. (2020). Innovative metallic microfluidic device for intensified biodiesel production. *Industrial and Engineering Chemistry Research*, *59*(1), 389–398. https://doi.org/10.1021/acs.iecr.9b04892

Emma, A. F., Alangar, S., & Yadav, A. K. (2022). Extraction and characterization of coffee husk biodiesel and investigation of its effect on performance, combustion, and emission characteristics in a diesel engine. *Energy Conversion and Management: X*, *14*, 100214. https://doi.org/https://doi.org/10.1016/j.ecmx.2022.100214

González, B., Calvar, N., Gómez, E., & Domínguez, Á. (2007). Density, dynamic viscosity, and derived properties of binary mixtures of methanol or ethanol with water, ethyl acetate, and methyl acetate at T = (293.15, 298.15, and 303.15) K. *Journal of Chemical Thermodynamics*, *39*(12), 1578–1588. https://doi.org/10.1016/j.jct.2007.05.004

Hajjari, M., Tabatabaei, M., Aghbashlo, M., & Ghanavati, H. (2017). A review on the prospects of sustainable biodiesel production: A global scenario with an emphasis on waste-oil biodiesel utilization. *Renewable and Sustainable Energy Reviews*, *72*(November 2016), 445–464. https://doi.org/10.1016/j.rser.2017.01.034

Hanif, M., Harahap, F. A. U., Heru, H., Darni, Y., & Ginting, S. B. (2019). Extraction and characterization of coffee oil from instant-coffee waste. *Jurnal Bahan Alam Terbarukan*, *8*(1), 59–64. https://doi.org/10.15294/jbat.v8i1.18619

Ismail, M., Fartaj, A., & Karimi, M. (2013). Numerical investigation on heat transfer and fluid flow behaviors of viscous fluids in a minichannel heat exchanger. *Numerical Heat Transfer; Part A: Applications*, *64*(1), 1–29. https://doi.org/10.1080/10407782.2013.773803

Jadhav, P. H., G, T., Gnanasekaran, N., & Mobedi, M. (2022). Performance score based multi-objective optimization for thermal design of partially filled high porosity metal foam pipes under forced convection. *International Journal of Heat and Mass Transfer*, *182*. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121911

Madhawan, A., Arora, A., Das, J., Kuila, A., & Sharma, V. (2018). Microreactor technology for biodiesel production: a review. *Biomass Conversion and Biorefinery*, *8*(2), 485–496. https://doi.org/10.1007/s13399-017-0296-0

Maji, A., & Choubey, G. (2020). Improvement of heat transfer through fins: A brief review of recent developments. *Heat Transfer*, *49*(3), 1658–1685. https://doi.org/10.1002/htj.21684

Meher, L. C., Vidya Sagar, D., & Naik, S. N. (2006). Technical aspects of biodiesel production by transesterification - A review. *Renewable and Sustainable Energy Reviews*, *10*(3), 248–268. https://doi.org/10.1016/j.rser.2004.09.002

Nedumaran, M. S., Trilok, G., Gnanasekaran, N., & Hooman, K. (2024). Multi-objective optimization of hybrid heat sinks with phase change materials. *Heat Transfer Engineering*, *45*(11), 1028–1049. https://doi.org/10.1080/01457632.2023.2234770

Ning, M., Mengjie, S., & Shiming, D. (2016). *Application of TOPSIS method in evaluating the effects of supply vane angle of a task / ambient air conditioning system on energy utilization and thermal comfort*. *180*, 536–545. https://doi.org/10.1016/j.apenergy.2016.08.011

Pandit, J., Thompson, M., Ekkad, S. V., & Huxtable, S. T. (2014). Effect of pin fin to channel height ratio and pin fin geometry on heat transfer performance for flow in rectangular channels. *International Journal of Heat and Mass Transfer*, *77*, 359–368. https://doi.org/10.1016/j.ijheatmasstransfer.2014.05.030

Pina, A., Ferrão, P., Fournier, J., Lacarrière, B., & Corre, O. Le. (2019). Waste coffee oil : A promising source for Heating biodiesel production Waste coffee oil : A promising source for biodiesel production MN Uddin the Assessing of using b the heat demand-outdoor temperature function for a long-ter. *Energy Procedia*, *160*, 677–682. http://dx.doi.org/10.1016/j.egypro.2019.02.221

Salman, S. D. (2019). Comparative study on heat transfer enhancement of nanofluids flow in ribs tube using CFD simulation. *Heat Transfer - Asian Research*, *48*(1), 148–163. https://doi.org/10.1002/htj.21376

Santacesaria, E., Di Serio, M., Tesser, R., Turco, R., Tortorelli, M., & Russo, V. (2012). Biodiesel process intensification in a very simple microchannel device. *Chemical Engineering and Processing: Process Intensification*, *52*, 47–54. https://doi.org/10.1016/j.cep.2011.12.001

Santana, H. S., Júnior, J. L. S., & Taranto, O. P. (2015). Numerical simulations of biodiesel synthesis in microchannels with circular obstructions. *Chemical Engineering and Processing: Process Intensification*, *98*, 137–146. https://doi.org/10.1016/j.cep.2015.10.011

Santana, H. S., Tortola, D. S., Reis, É. M., Silva, J. L., & Taranto, O. P. (2016). Transesterification reaction of sunflower oil and ethanol for biodiesel synthesis in microchannel reactor: Experimental and simulation studies. *Chemical Engineering Journal*, *302*, 752–762. https://doi.org/10.1016/j.cej.2016.05.122

Sarafraz, M. M., & Christo, F. C. (2021). Thermal and flow characteristics of liquid flow in a 3D-printed micro-reactor: A numerical and experimental study. *Applied Thermal Engineering*, *199*(June). https://doi.org/10.1016/j.applthermaleng.2021.117531

Sime, W., Kasirajan, R., Latebo, S., Mohammed, A., & Seraw, E. (2017). Coffee husk highly available in ethiopia as an alternative waste source for biofuel production. *International Journal of Scientific & Engineering Research*, *8*(7), 1874–1880. http://www.ijser.org

Tiwari, A., Rajesh, V. M., & Yadav, S. (2018). Energy for Sustainable Development Biodiesel production in micro-reactors : A review. *Energy for Sustainable Development*, *43*, 143–161. https://doi.org/10.1016/j.esd.2018.01.002

Verma, R. K., & Ghosh, S. (2021). Curvature induced intensification of biodiesel synthesis in miniature geometry. *Chemical Engineering and Processing - Process Intensification*, *163*(January). https://doi.org/10.1016/j.cep.2021.108363

Xia, G., Chen, Z., Cheng, L., Ma, D., Zhai, Y., & Yang, Y. (2017). Micro-PIV visualization and numerical simulation of flow and heat transfer in three micro pin-fin heat sinks. *International Journal of Thermal Sciences*, *119*, 9–23. https://doi.org/10.1016/j.ijthermalsci.2017.05.015

Zhao, J., Huang, S., Gong, L., & Huang, Z. (2016). Numerical study and optimizing on micro square pin-fin heat sink for electronic cooling. *Applied Thermal Engineering*, *93*, 1347–1359. https://doi.org/10.1016/j.applthermaleng.2015.08.105