

Contents lists available at: <http://qu.edu.iq>

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: <https://qjes.qu.edu.iq>

Review Paper

A critical review of forced convection in microchannels

Ghufran Kadhim and Ahmed Al-Saadi  

Department of Mechanical Engineering, College of Engineering, University of Al-Qadisiyah, Al-Diwaniyah, Iraq.

ARTICLE INFO

Article history:

Received 07 March 2023

Received in revised form 25 December 2024

Accepted 03 July 2025

keyword:

Microchannel

Laminar

Heat transfer

CFD simulation

Thermal analysis

ABSTRACT

The dissipation of excessive heat flux is presently a significant issue that needs to be addressed due to the use of microdevices in fields such as nuclear energy, electronic devices, aerospace engineering, building engineering, and more. Because of their increased heat transfer and compact size, microchannel cooling systems have become an effective way to manage the temperature of microdevices and equipment upgrades. However, due to the increasing demands placed on microdevices for thermal load, controlling the temperature, and conserving energy, efficient heat exchangers, in particular microchannels, are attracting a growing amount of interest. A key passive technique for successfully increasing the heat transfer of the microchannel cooling system and improving the performance of microchannels is channel shape optimization. Therefore, the characteristics of microchannel geometry from prior research have been reviewed, categorized, and summed up in this article. The analysis focuses primarily on structural features and microchannel geometry attributes that enhance the impact of pressure drop and heat transfer. It also presents the relationship between boiling heat transfer and the geometrical features of microchannel flow and discusses the potential study directions for microchannel geometry design. The current review of microchannels will provide researchers working on these microchannel components with specialized expertise. In an effort to improve the impact of heat transfer, this study reviews, categorizes, and summarizes the characteristics of prior studies' microchannel geometry.

© 2025 University of Al-Qadisiyah. All rights reserved.

1. Introduction

Over the past 40 years, the fields of microfluidics and biomedicine have shown a great deal of interest in microchannels based on Micro Electromechanical Systems (MEMS). Tuckerman et al. [1] first suggested the microchannel heat rejection concept in 1981 to address the issue of heat dissipation in extremely small integrated circuits with up to 790 W/cm² of massive heat dissipation capabilities. Microdevices have been utilized in a variety of industries applications, e.g., aerospace industry [2], chemical engineering [3], physical particle separation [4], nuclear energy [5], inkjet print heads [6], electronic devices [7], heat exchangers for cooling computer chips [8], building engineering [9], and biological engineering [10]. Fluid flows in all types of channels and machined fluid systems are numerically analysed by using the Navier-Stokes equations [11]. However, some previous studies have shown that flows on the microchannel are different from that on the macrochannel. Therefore, using the Navier-Stokes equations only in numerical analysis of flow in microchannel cannot provide a clear and correct simulations [12]. As a result, a greater comprehension of fluid flow at the microscopic level is required in order to design and manufacture such microdevices efficiently. Moharana et al. [13] looked at the heat transmission properties of microchannels with a rectangular shape. Aspect ratio, distance from center to center, velocity of the fluid, and their effects on heat transmission were among the variables used. Water flowing through a trapezoidal-shaped microchannel with a hydraulic diameter ranging from 62 μm to 169 μm was the subject of an investigation by Qu et al. [14]. A new class of designed heat transfer fluids with metallic or carbon-based particles with an average size of about 10 μm are referred to as nanofluids, according to Choi et al. [15]. According to Koo and Kleinstreuer, the word "nanofluids" refers to a brand-new class of tailored

heat transfer fluids containing particles with a mean size of roughly 10 nm made of metal or carbon [16]. Zhang et al. altered the microchannel cooling system with two phases to generate a 969 W/cm² critical heat flow [17]. Kim et al. [18] achieved a heat flux of up to 2 kW/cm² using a two-phase dedicated hot-spot cooler, whereas Tang et al. developed microchannels with single and three expansion areas for comparison. According to experimental findings, adding three expansion areas to microchannels can significantly up to 43.3% more flow-boiling heat transfer efficiency [19]. The significance of researching microscale phenomena in engineering has only recently increased, despite the fact that the study of fluid flow and heat transmission in channels with incredibly tiny hydraulic mean diameters has long drawn attention [20]. The smaller channels are defined by the hydraulic diameter. Microchannels are channels with a maximum polygonal cross-sectional area of less than 1 mm and hydraulic diameters of 10 to 200 μm [21]. Figure 1 shows some kind of cross-sectional area of microchannels used in engineering applications. We must utilize a cooling system that is applicable to the same scale as electronic components get smaller at the micro/mini scale. Among the most suitable options for tiny cooling is fluid movement inside micro and tiny channels. According to this, the hydraulic diameter (D_H) is used to categorize micro and tiny [22]. Table 1 illustrates the difference between minichannels and microchannels. According to the scaling law, when compactness rises, heat transmission rises, and pressures fall as well. Hence, a larger heat transfer coefficient results in a greater pressure drop, which increases the need for pumping power. By increasing the hydraulic diameter from micro to various small-scale configurations, we are able to achieve a heat transfer coefficient that is adequate at a significantly lower pressure drop for a specific system application [23].

* Corresponding Author.

E-mail address: ahmed.shakir@qu.edu.iq ; Tel: (+964) 780-600 7641 (Ahmed Al-Saadi)



Nomenclature

A	Cross-sectional area of the conduit or channel
D_H	Hydraulic diameter for all types of ducts
P	Wetted perimeter
Re	Reynolds number
T	Temperature
V	Velocity of the fluid

Greek Symbols

μ	Fluid's dynamic viscosity
ρ	Density of the fluid
∇	Gradient
$\vec{U}$	Velocity vector field of a fluid

Several media, including liquid, gas, and air, can be used to cool electronics. In the past years, people favoured using air and water to cool off [24]. When compared to water, which has a higher density and a higher heat capacity, air has a lesser heat carrying capacity and is almost at its thermal maximum of roughly 100 W/cm^2 . Therefore, water cooling rather than air cooling is employed to remove high heat flux. Today, a variety of different liquids are used instead of water [25]. Two-phase flow has a higher pressure decrease than single-phase flow, and both strategies have advantages and limitations. Two-phase flow with a single component can transmit more heat than one-phase flow when a substance is boiling. These previous articles [26,27] focused on the movement of a single-phase liquid in a tiny channel. The thermophysical characteristics of different fluids have been compared and studied to better understand the heat transfer mechanism. Fluid and flow parameters have an impact on the convective heat transfer coefficient. The mass flow rate, fluid specific heat, shape, and roughness of the channel's surface all significantly affect how fluids behave.

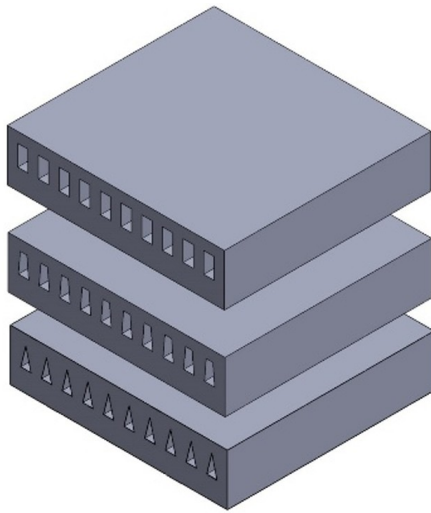


Figure 1. Three different types of microchannel cross-sectional area.

Table 1. Listed the distinction between minichannels and microchannels.

Type of channel	Hydraulic diameter D_H
Minichannels	$3\text{mm} \geq D_H > 200\mu\text{m}$
Microchannels	$200\mu\text{m} \geq D_H > 10\mu\text{m}$

2. Fundamentals of heat transfer

This section will provide a review of the fundamentals of flow and heat transport in microchannels performed in recent years using cutting-edge conventional CFD methodology as well as experimental work. Heat transfer is a process that provides thermal energy from a hotter body to a colder body. This may happen between two or more physical objects or systems [28]. Heat transfer is a scientific discipline that serves as a foundation for several scientific and engineering fields, such as mechanical engineering, chemical engineering, materials science, physics, and electrical engineering etc. Analysis of heat transfer properties is based on both experimental and theoretical approaches [29]. Models and numerical simulation tools have been established over time with laboratory tests to explore the heat transfer mechanisms with more precision and efficiency. Heat transfer investigations are still of paramount interest in a variety of industrial processes. Its importance is increasing through technological development and new engineering problems [30].

2.1 Reynolds number

The Reynolds number is a dimensionless quantity that is used to indicate how laminar, transitional, or turbulent the fluid flow is. It represents the ratio of inertial to viscous forces in a fluid [31,32]. The following formula represents the Reynolds number, Eq. 1.

$$Re = (\rho/\mu)VD_H \quad (1)$$

If the Reynolds number is less than 2300, this indicates that the flow is laminar. While if it is more than 4000, this means the flow is turbulent. Some cases have Reynolds numbers between 2300 and 4000; these types of flows may transition between laminar and turbulent depending on changing conditions [33]. In general, fluid particles in laminar flow travel in a predictable and ordered pattern. On the other hand, the fluid particles in turbulent flow are moving in an erratic and chaotic way. Figure 2 illustrates laminar, turbulent, and transition boundary layers.

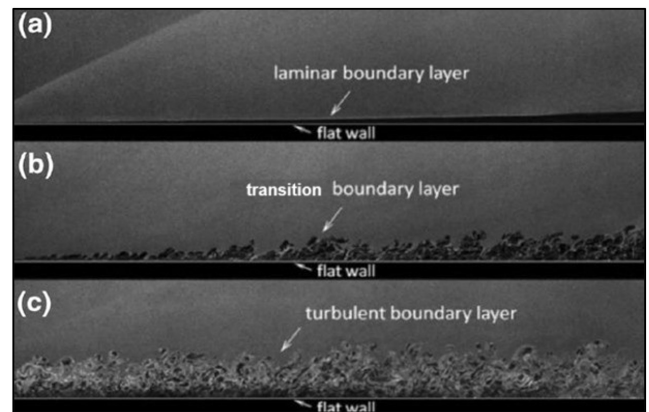


Figure 2. All types of boundary layers.

2.2 Type of flow

An interesting phenomenon, fluid flow is significant in several engineering and scientific applications. The investigation and analysis of how fluids move through different media, such as pipes, channels, and ducts, is a key component of the study of fluid flow [34]. Understanding fluid flow is crucial and needed in order to design and improve systems containing fluid materials, such as pumps, pipelines, turbines, etc. There are various fluid flow patterns, and each has certain traits and ramifications [35]. Laminar flow, turbulent flow, transitional flow, and steady flow are a few examples of these fluid flow types. Some previous studies examined each kind of fluid flow, went over its characteristics, and explained how it affects various applications [36,37]. A laminar fluid flow is characterized as a flow type in which the fluid particles travel along distinct, straight, parallel streamlines. The particles consequently move in layers or laminas, gently sliding over one another [38]. This kind of flow is also referred to as smooth flow and flows with viscosity. A turbulent fluid flow is characterized by the zig-zag motion of the fluid particles. A significant part of energy is lost due to eddy generation [39]. This type of fluid flow is calculated for pipe flow by a Reynolds number, which is a dimensionless quantity [40]. The flow is laminar when the Reynolds number is less than 2000. While it is turbulent when the Reynolds number is greater than 4000. In the range of Reynolds between 2000 and 4000, the flow could be laminar and turbulent. Understanding a variety of kinds of fluid flow is important in a range of studies, including science, engineering, and medicine [41]. The overall behavior of fluids under different conditions is affected by the diverse properties of laminar, transitional, and turbulent flow. Laminar flow is smooth and predictable, while turbulent flow is disorderly and unpredictable [42]. Transitional flow presents characteristics of both laminar and turbulent flows. Each of these three kinds of regimes of flow has advantages and limitations. The properties of fluid flow, such as velocity, density, and viscosity, can affect how each type of flow

behaves [43]. In many applications Fig. 3, including aerodynamics, hydraulics, and blood flow in the human body, effective fluid flow management is essential for achieving optimal efficiency and performance [44]. To achieve the optimal efficiency, fluid systems can be designed with an understanding of the different types of fluid flow. In general, fluid flow field is a difficult and challenging subject that needs to understand the physical characteristics of fluids and their behavior under different conditions [45].

2.3 Hydraulic diameter

The hydraulic diameter represents a measure of the effective internal diameter of any cross-sectional area of pipe or channel. It is a ratio of four times the cross-sectional area of the pipe to its wetted perimeter [46]. It can be expressed mathematically, Eq. 2.

$$D_H = 4(A/P) \quad (2)$$

The hydraulic diameter is useful for determining the fluid flow characteristics inside pipes, such as the friction factor and Reynolds number [47]. The hydraulic diameter is used when dealing with non-circular pipes or channels, as it provides an equivalent diameter that can be used in calculations as if the flow were occurring in a circular pipe or channel. For example, the hydraulic diameter of a rectangular cross-sectional pipe may be used as the equivalent diameter of a circular cross-sectional pipe to calculate the friction factor [48]. Another important application of using hydraulic diameter is the calculation of heat transfer for different geometries. In these cases, the hydraulic diameter is used to calculate the heat transfer coefficient and overall heat transfer rate [49]. In summary, hydraulic diameter is an important parameter for calculations of fluid flow and heat transfer in non-circular pipes or channels by providing an equivalent measure of the internal diameter that can simplify calculations and comparisons between different systems [50].

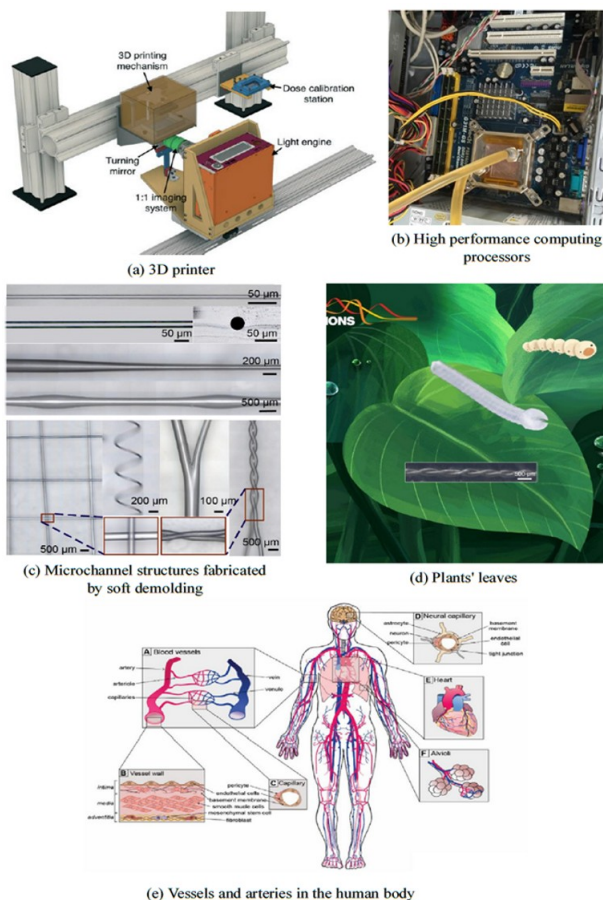


Figure 3. Some applications of microchannel flow.

2.4 Governing equations

The Navier-Stokes equations and the energy equation are used to calculate all fluid flow properties and heat transfer. Most studies of heat transfer inside

microchannels neglect radiation calculations to simplify the solutions. Continuity, momentum, and energy equations used in this field are listed in Eq. 3, [51].

$$\begin{aligned} \nabla \cdot [\rho_l \vec{U}] &= 0 \\ \nabla \cdot [\rho_l \vec{U} \vec{U}] &= -\nabla P + \nabla \cdot [\mu_l \nabla \vec{U}] \\ \nabla \cdot [\rho_l \vec{U} T] &= \nabla \cdot \left[\frac{k_l}{C_{p,l}} \nabla T \right] \end{aligned} \quad (3)$$

3. Methods of solution

Computational Fluid Dynamics (CFD) simulations and experimental techniques can both be used to calculate all properties of fluid flow inside a microchannel. Some researchers prefer to use computational fluid dynamics (CFD) simulations [52–59], while others use experimental techniques [60, 61]. In general, both techniques are useful to study the flow inside microchannels, and each of them has advantages and limitations. Available resources are the main key to choosing methodology [51, 62, 63].

3.1 Experimental

Some experimental techniques use microscopic particles suspended in the fluid to visualize the flow patterns of the fluid. Another technique is used to measure the pressure drop across a microchannel at a known flow rate to determine the flow resistance. Experimental techniques need specialized equipment and are typically time-consuming and expensive [60, 61, 64].

3.2 Numerical

The simulation involves creating geometry, creating a mesh, setting up boundary conditions, and solving the governing equations of fluid flow using numerical methods. The simulation can provide a very accurate prediction of the velocity, pressure, temperature, and other properties inside the microchannel. The accuracy of CFD simulations depends on many things, such as boundary conditions, type of mesh, and setup [52–59].

3.2.1 COMSOL software

COMSOL is a great engineering software for modeling and simulating complex physical systems in a wide range of scientific and engineering fields [65]. It allows researchers to create different virtual models, such as fluid dynamics, heat transfer, chemical reactions, and electromagnetics. It can simulate how all these models behave under different conditions. Academic study, industry, and research institutions have used COMSOL software to create different geometries and optimize new products and processes through simulations. COMSOL helps to improve our understanding of the natural world [65]. The biggest advantage of the COMSOL software is that it can be used easily, and it has some of the important key features [65].

3.2.2 Ansys software

Ansys software is widely used in engineering and physics fields for numerical simulations. Researchers can simulate and analyze huge cases in different fields by using finite element analysis [66, 67]. A lot of studies of stress and strain, fluid dynamics, heat transfer, electromagnetic fields, and more are using this software. It offers a variety of tools and features to create and simulate complex models, and its powerful solver technology can accurately simulate real cases [68, 69]. Ansys contains mesh generation tools and a wide range of turbulent models; therefore, huge academic studies depend on this software in numerical studies.

3.2.3 MATLAB

MATLAB is widely used in computational fluid dynamics [70]. It can be used to solve different fluid dynamics problems, including laminar and turbulent flow, heat transfer, and multiphase flow. However, the usage of MATLAB in fluid flow requires a deep knowledge of the tools of the program [71]. The main steps to using MATLAB in simulations of fluid flow are as follows: Define the problem and set up the governing equations [72]. Then, categorize the governing equations using finite difference, finite volume, or finite element techniques [73]. After that, write a code depending on which technique you use [74]. Then, define the initial and boundary conditions for the case problem [75]. The next step is to run the code simulation to solve the governing equations for the fluid flow variable within the entire domain [76].

4. Geometric design of channels

Geometric design of pipes and channels is the process of determining the optimal shape and dimensions of that pipe or channel required. The optimal design of a pipe or channel means efficient and safe transport of water or other fluids [77]. The main points in design involve consideration of various factors such as flow rate and hydraulic efficiency. It requires an understanding of fluid mechanics and hydraulic principles. Geometric design of pipes or channels typically includes determining the cross-section, length, arrangement, and slope measures [78].

4.1 Channels

A channel or pipe is typically a long enough, narrow, and enclosed structure that is used to control the fluid flow, such as water, gas, or oil [79]. The great design of a pipe or channel should provide efficient flow with minimal energy loss due to friction. The main points of any design are the shape and dimensions [80]. Determining the flow rate and the properties of the fluid that will be transported is the first step in designing a channel. In addition to including the viscosity, density, and temperature of the fluid [81, 82]. The most common cross-sectional shapes of pipes and channels are circular, rectangular, and trapezoidal [83]. The shape of the pipe or channel is determined by the flow rate of the fluid and the conditions that the pipe or channel will be installed on [84]. The hydraulic diameter is a significant factor in the design process of a pipe or channel. It can be calculated as the ratio of four times the channel's cross-sectional area to its wetted perimeter [85]. The length of contact between fluids and all ribs that make up the boundary of the cross-sectional area is called the wetted perimeter. To calculate the flow rate and the velocity of the fluid flow, the hydraulic diameter is used. To achieve efficient flow, the slope of the pipe or channel would be chosen correctly [86]. The change in elevation of the pipe position over a certain distance is called slope or gradient. It should be steep enough to maintain flow but not so steep that there is excessive erosion or turbulence [87]. In general, the cross-sectional design as well as the suitable length of a channel is important in ensuring the efficient and safe transportation of fluids. Choosing the shape of the cross-sectional area and its dimensions, the length of the channel, and the slope of the channel must be selected carefully to ensure that the channel works as designed and delivers the fluid to its target destination with minimal energy loss [88].

4.2 Minichannels

A mini-channel has a geometry design that is a narrow and compact channel that is used to transport any type of fluid. Mini-channels are usually used in microfluidic devices for a wide range of uses, including chemical analysis, medical diagnosis, and drug delivery [89].

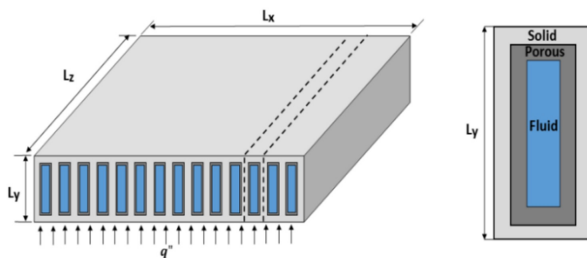


Figure 4. Rectangular microchannel heat sink.

The design and size of mini-channels are unique and differ significantly from ordinary channels. The overall size of the mini-channel is typically less than a millimeter in diameter, which means that the properties of flow reveal different behavior than ordinary channels. The fluid flow in mini-channels is laminar due to the low maximum velocity of flow, meaning that the flow inside the mini-channel is streamlined without any turbulence [90]. There are a lot of different geometries of mini-channels used depending on the specific application. However, the most common design shapes of cross-sectional area in mini-channels are rectangular and circular. The mini-channel with the rectangular cross-section has a maximum surface area, which means maximum heat transfer. This reason is enough to select this type in applications of heat transfer and chemical reactions [91]. On the other hand, circular channels have some advantages, such as being easy to make, having a low pressure drop, and having a more uniform flow. Mini-channel design is typically characterized by its aspect ratio, which is the ratio of the channel's height or width to the length of the mini-channel [92]. The flow properties and pressure drop inside

mini-channels depend on the aspect ratio. Therefore, the aspect ratio is a critical factor in the design process. If the mini-channel has a lower aspect ratio, then it can have lower pressure drops and is more suitable for microfluidic applications such as lab-on-a-chip devices [93, 94].

4.3 Microchannels

A microchannel has a special geometry design so that its dimensions are very small. A tiny passage in the microchannel with a hydraulic diameter less than 1 millimeter is used for some important applications that need the controlled flow of fluids. Microfluidic devices, heat exchangers, and chemical reactors are the most common applications of minichannels [95]. There are different geometries available for microchannels which are selected based on the application and its requirements [57, 96, 97]. Some common geometries of microchannels are:

4.3.1 Rectangular microchannel

Rectangular microchannels are widely used in microfluidics applications, as they provide a more significant surface area for fluid-solid interaction and thermal exchange. Many previous studies used a rectangular cross-sectional area in microchannels because it has a lot of advantages [98–104]. The aspect ratio (channel height to width ratio) of rectangular microchannels usually ranges from 0.1 to 10 [105]. Figure 4 shows the rectangular microchannel heat sink and its computational domain [106].

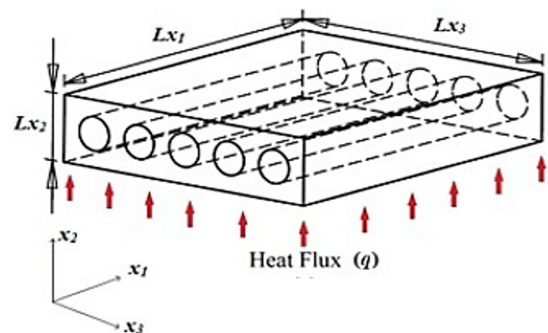


Figure 5. Circular microchannel heat sink.

4.3.2 Circular microchannels

Circular microchannels offer some benefits over rectangular channels, like more straightforward fabrication, easier cleaning, and lower surface area to volume ratios. Because it has numerous advantages, circular cross-sectional areas of microchannels have been used in many prior research [102, 103, 107]. However, circular channels may suffer from uneven fluid flow distribution and reduced heat transfer efficiency [108]. Figure 5 shows the circular microchannel heat sink [109].

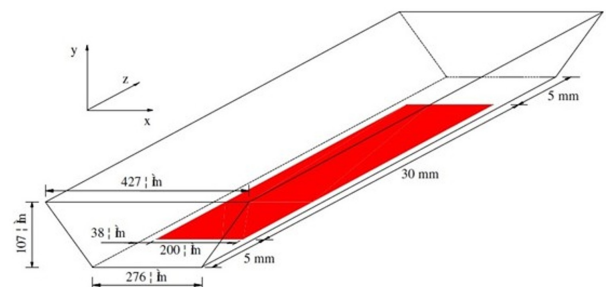


Figure 6. Trapezoidal microchannel heat sink.

4.3.3 Trapezoidal microchannels

Trapezoidal microchannels offer better fluid-dynamics performance than rectangular or circular microchannels [103, 104, 110, 111]. They have a higher thermal exchange capability as they have a larger surface area [112]. Figure 6 shows the trapezoidal microchannel heat sink [51].

4.3.4 Triangular microchannels

Triangular microchannels offer better fluid mixing due to their unique geometry that provides swirling flows and a larger contact surface with the walls

[100–102, 104]. This cross-sectional design leads to the creation of a laminar flow pattern, and it has the lowest pressure drop compared to other microchannel geometries [113]. This type of microchannel has a lot of uses, such as in microfluidic devices for various biomedical applications. These applications can be such as drug delivery, lab-on-a-chip systems, and cell analysis. The large ratio of surface area to volume in this type of microchannel provides high fluid pressure drop, efficient mixing, and increased heat transfer rates. In general, triangular microchannels have become a popular tool in scientific research and development. Figure 7 illustrates a triangular microchannel heat sink [114].

4.3.5 Elliptic microchannels

An elliptic microchannel is a kind of microchannel with an elliptical cross-sectional design. It can be used for many applications, such as microfluidic devices, chemical sensors, and heat exchangers. One of the biggest advantages is having a lower pressure drop compared to circular microchannels with the same hydraulic diameter. Microchannels with elliptic cross-sectional area have a higher surface-to-volume ratio than circular microchannels, and that can lead to higher heat transfer rates [100, 101]. Figure 8 shows a sample of an elliptic microchannel heat sink [115].

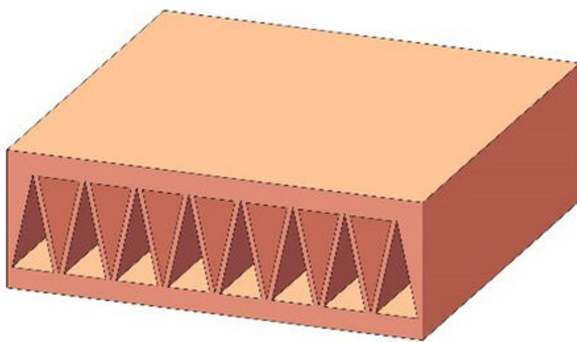


Figure 7. Triangular microchannel heat sink.

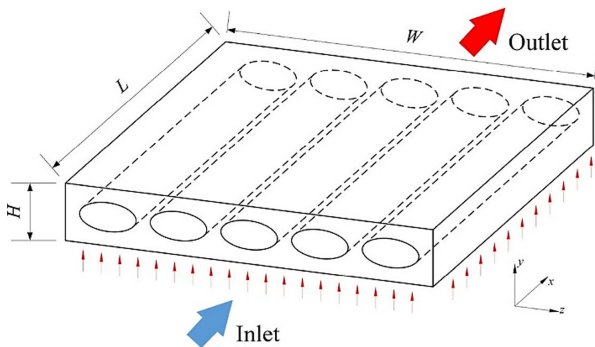


Figure 8. Elliptic microchannel heat sink.

5. Cooling fluid

Any liquid that is used to transfer heat away from any hot body or surface to keep it from overheating is called a coolant or cooling fluid. A hot body can be an engine or other machinery component. The cooling process circulates through a closed system of pipes and connections to absorb heat generated by the engine, heat source, or machinery, and then rejects this heat to the air by using a heat exchanger or radiator. There are a lot of types of coolants, and each of them can have different viscosities, colors, and other properties. Cooling fluid keeps machinery from freezing in cold temperatures and melting in very high temperatures. Many types of cooling fluids are available for different applications. Usually, coolant is made from a mixture of water and antifreeze or ethylene glycol [116–118].

5.1 Air

Most dissipating heat processes from a fluid use air as a cooling medium. In the cooling process, heat is transferred from a higher temperature (fluid) to a lower temperature (air), which can carry the heat away [119]. Many applications

use the air-cooling process, such as car engines, electronic devices, industrial processes, and power plants. Most of these applications used a heat exchanger where heated fluid is passed inside a heat exchanger while air works to cool the external surfaces of the heat exchanger [120]. After the fluid loss, its heat can circulate back into the system. All air that passes through the heat exchanger is rejected externally [121]. Three types of air cooler processes are forced-air coolers, natural convection coolers, and hybrid coolers [122]. If air is forced to move over the heat exchanger by using a fan or blower, then the process is called forced-air cooling [123]. Any system without any external device to force the air is called a natural convection cooler [124]. Hybrid coolers combine forced-air coolers and natural convection coolers. A fan or blower is used to enhance natural convection [125]. Using the air-cooling technique has some advantages, which are low maintenance, lower cost, and portability [126]. On the other hand, the air-cooling technique has some limitations, such as lower heat transfer efficiency compared to the liquid cooling technique and reduced performance in high-temperature environments [127]. The efficiency of air-cooling techniques depends on some parameters such as airflow rate, ambient temperature, and cooling system design [128, 129].

5.2 Water

In the last years, several researchers studied the application of water as a medium in microchannel heat sinks. Water in microchannels has many important applications, such as electronics cooling, chemical and biological analysis, and microfluidic devices [130, 131]. The flow rate of water inside the microchannel heat sink is significantly reduced because of the small cross-sectional area. And that can improve efficiency and control of temperature. This is a great idea with small amounts of fluids or biological samples. Flowing of water inside microchannels shows higher convective heat transfer coefficients than bulk fluids because of the higher velocity of water near the microchannel walls [99, 101]. This phenomenon can lead to improved cooling capacity, making microchannels an excellent choice for thermal management in electronics and other applications [104, 132].

5.3 Ethanol

Using ethanol as a cooling fluid inside microchannels is not recommended because it has a low boiling point and may cause risks of flammability and safety hazards. Ethanol is dangerous and must be handled with particular care because it is a highly flammable substance [133]. Therefore, very few researchers used ethanol. And it is recommended to use alternative cooling fluids. They are specifically designed for cooling applications [134]. Ethanol has another limitation, which is low specific heat capacity. It can only absorb a smaller amount of heat energy per unit mass, so using it as a cooling fluid can also be ineffective [135]. More quantity of ethanol is required to cool a given system, which means it is more expensive than other cooling fluids. Another significant limitation of ethanol is that it is corrosive and can damage some materials [136]. This point can lead to leaks and decreased system efficiency because most cooling systems have rubber, plastic, and some metals. In general, using ethanol as a cooling fluid in industrial applications is not recommended because it has many limitations [137].

6. Conclusion

This study offers a thorough, current analysis of flow and heat distribution in microchannels. This article aims to inspire scientists to focus more on the performance of heat exchanger systems by encouraging them to analyze heat transfer in microchannels. Circular microchannels are more efficient than rectangular channels in terms of straightforward fabrication and easier cleaning. Trapezoidal microchannels offer better fluid-dynamic performance than rectangular or circular microchannels because they have a larger surface area, which leads to a higher thermal exchange capability. Elliptic cross-sectional area provides lower pressure drop compared to circular microchannels, and that leads to higher heat transfer rates. There are many software programs used to simulate the flow and heat transfer in all types of channels. The overall behavior of fluid flow inside the channel and microchannel is not similar. Case in point: the hydrodynamic and thermal entrance regions in microchannels are smaller than in channels. The other conclusion that can be reached from the currently available data is that water is the best medium for heat exchangers in microchannels, while ethanol has many limitations. The highest heat transfer occurs in the entrance region of microchannels, and it decreases as the flow moves away from the entrance because the thickness of the boundary layer is as small as possible from the beginning of the inlet of the microchannel and then increases with the direction of flow.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- [1] D. Tuckerman and R. Pease, "High-performance heat sinking for vlsi," *IEEE Electron Device Letters*, vol. 2, no. 5, pp. 126–129, 1981. [Online]. Available: <https://doi.org/10.1109/EDL.1981.25367>
- [2] H. Stone and S. Kim, "Microfluidics: basic issues, applications, and challenges," *American Institute of Chemical Engineers(AIChE Journal)*, vol. 47, no. 6, pp. 1250–1254, 2001. [Online]. Available: <https://doi.org/10.1002/aic.690470602>
- [3] D. Garrett, "Chemical engineering economics," *Springer Science Business Media*, 2012. [Online]. Available: <https://doi.org/10.1007/978-94-011-6544-0>
- [4] R. Nasiri, A. Shamloo, S. Ahadian, L. Amirifar, J. Akbari, M. Goudie, K. Lee, N. Ashammakhi, M. Dokmeci, D. Di-Carlo, and A. Khademhosseini, "Microfluidic-based approaches in targeted cell/particle separation based on physical properties: Fundamentals and applications," *Small*, vol. 16, no. 29, p. 2000171, 2020. [Online]. Available: <https://doi.org/10.1002/smll.202000171>
- [5] F. Whicker and V. Schultz, "Radioecology: nuclear energy and the environment," *Boca Raton, FL: CRC press, Inc.*, vol. 1, no. 1, pp. 75–150, 1982. [Online]. Available: <file:///C:/Users/RS3/Downloads/10462.pdf>
- [6] L. Creagh and M. McDonald, "Design and performance of inkjet print heads for non-graphic-arts applications," *MRS bulletin*, vol. 28, no. 11, pp. 807–811, 2003. [Online]. Available: <https://doi.org/10.1557/mrs2003.229>
- [7] M. Shur, "Introduction to electronic devices," *J. Wiley.*, p. 604, 1996. [Online]. Available: <https://doi.org/10.1002/9781118133333>
- [8] K. Ma and J. Liu, "Heat-driven liquid metal cooling device for the thermal management of a computer chip," *Journal of Physics D: Applied Physics*, vol. 40, no. 2007, pp. 4722–4729, 2007. [Online]. Available: <https://doi.org/10.1088/0022-3727/40/15/055>
- [9] Z. Yu, F. Haghighat, and B. Fung, "Advances and challenges in building engineering and data mining applications for energy-efficient communities," *Sustainable Cities and Society*, vol. 25, pp. 33–38, 2016. [Online]. Available: <https://doi.org/10.1016/j.scs.2015.12.001>
- [10] Y. Huang, Y. Lan, S. Thomson, A. Fang, W. Hoffmann, and R. Lacey, "Development of soft computing and applications in agricultural and biological engineering," *Computers and Electronics in Agriculture*, vol. 71, no. 2, pp. 107–127, 2010. [Online]. Available: <https://doi.org/10.1016/j.compag.2010.01.001>
- [11] K. Khadra, P. Angot, S. Parneix, and J. Caltagirone, "Fictitious domain approach for numerical modelling of navier–stokes equations," *International Journal for Numerical Methods in Fluids*, vol. 34, no. 8, pp. 651–684, 2000. [Online]. Available: [https://doi.org/10.1002/1097-0363\(20001230\)34:8\(651::AID-FLD61\)3.0.CO;2-D](https://doi.org/10.1002/1097-0363(20001230)34:8(651::AID-FLD61)3.0.CO;2-D)
- [12] V. Siva, A. Pattamatta, and S. Das, "Investigation on flow maldistribution in parallel microchannel systems for integrated microelectronic device cooling," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 4, no. 3, pp. 438–450, 2013. [Online]. Available: <https://doi.org/10.1109/TCPMT.2013.2284291>
- [13] M. Moharana, N. Peela, S. Khandekar, and D. Kunzru, "Distributed hydrogen production from ethanol in a microfuel processor: Issues and challenges," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 524–533, 2011. [Online]. Available: <https://doi.org/10.1016/j.rser.2010.08.011>
- [14] W. Qu, G. Mala, and D. Li, "Heat transfer for water flow in trapezoidal silicon microchannels," *International Journal of Heat and Mass Transfer*, vol. 43, no. 21, pp. 3925–3936, 2000. [Online]. Available: [https://doi.org/10.1016/S0017-9310\(00\)00045-4](https://doi.org/10.1016/S0017-9310(00)00045-4)
- [15] K. V. Prasad, S. R. Santhi, and P. S. Datti, "Non-newtonian power-law fluid flow and heat transfer over a non-linearly stretching surface," *Applied Mathematics*, vol. 3, no. 5, May 2012. [Online]. Available: <https://doi.org/10.4236/am.2012.35065>
- [16] J. Koo and C. Kleinstreuer, "Laminar nanofluid flow in microheat-sinks," *International Journal of Heat and Mass Transfer*, vol. 48, no. 13, pp. 2652–2661, 2005. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2005.01.029>
- [17] Y. Zhu, D. Antao, K. Chu, S. Chen, T. Hendricks, T. Zhang, and E. Wang, "Surface structure enhanced microchannel flow boiling," *Journal of Heat Transfer*, vol. 138, no. 9, pp. 5192– 5202, 2016. [Online]. Available: <https://doi.org/10.1115/1.4033497>
- [18] Y. Kim, Y. Joshi, A. Fedorov, Y. Lee, and S. Lim, "Thermal characterization of interlayer microfluidic cooling of three-dimensional integrated circuits with nonuniform heat flux," *ASME Journal of Heat and Mass Transfer*, vol. 132, no. 4, p. 041009(9p), 2010. [Online]. Available: <https://doi.org/10.1115/1.4000885>
- [19] J. Tang, Y. Liu, B. Huang, and D. Xu, "Enhanced heat transfer coefficient of flow boiling in microchannels through expansion areas," *International Journal of Thermal Sciences*, vol. 177, p. 107573, 2022. [Online]. Available: <https://doi.org/10.1016/j.ijthermalsci.2022.107573>
- [20] S. Kandlikar, S. Colin, Y. Peles, S. Garimella, R. Pease, J. Brandner, and D. Tuckerman, "Heat transfer in microchannels—2012 status and research needs," *ASME Journal of Heat and Mass Transfer*, vol. 135, no. 9, p. 091001(18page, August 2013. [Online]. Available: <https://doi.org/10.1115/1.4024354>
- [21] A. Alfaryjat, H. Mohammed, N. Adam, M. Ariffin, and M. Najafabadi, "Influence of geometrical parameters of hexagonal, circular, and rhombus microchannel heat sinks on the thermohydraulic characteristics," *International Communications in Heat and Mass Transfer*, vol. 52, pp. 121–131, 2014. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2014.01.015>
- [22] X. Chen, H. Ye, X. Fan, T. Ren, and G. Zhang, "2016. a review of small heat pipes for electronics," *Applied Thermal Engineering*, vol. 96, no. 5, pp. 1–17, May 2016. [Online]. Available: <https://doi.org/10.1016/j.applthermaleng.2015.11.048>
- [23] Y. Wang and K. Sefiane, "Effects of heat flux, vapour quality, channel hydraulic diameter on flow boiling heat transfer in variable aspect ratio micro-channels using transparent heating," *International Journal of Heat and Mass Transfer*, vol. 55, no. 9-10, pp. 2235–2243, 2012. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2012.01.044>
- [24] S. Kandlikar and C. Hayner, "Liquid cooled cold plates for industrial high-power electronic devices—thermal design and manufacturing considerations," *Heat transfer engineering*, vol. 30, no. 12, pp. 918–930, 2009. [Online]. Available: <https://doi.org/10.1080/01457630902837343>
- [25] V. Yadav, R. Kumar, and A. Narain, "Mitigation of flow maldistribution in parallel microchannel heat sink," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 9, no. 2, pp. 247–261, 2018, May. [Online]. Available: <https://doi.org/10.1109/ICASERT.2019.8934553>
- [26] K. Thakkar, K. Kumar, and H. Trivedi, "Thermal hydraulic characteristics of single-phase flow in mini-channel for electronic cooling—review," *Int. J. Innovative Research in Science, Engineering and Technology*, vol. 3, no. 2, pp. 9726–9733, 2014. [Online]. Available: <http://doi.org/10.15680/ijirser>
- [27] K. Nilpueng, T. Keawkamrop, H. Ahn, and S. Wongwises, "Effect of chevron angle and surface roughness on thermal performance of single-phase water flow inside a plate heat exchanger," *International Communications in Heat and Mass Transfer*, vol. 91, pp. 201–209, 2018. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.009>
- [28] P. Panigrahi, "Transport phenomena in microfluidic systems," *John Wiley Sons*, vol. 16, no. 3, pp. 1617–1634, 2016. [Online]. Available: <https://doi.org/10.1002/9781118298428>
- [29] V. Guichet, B. Delpech, and H. Jouhara, "Experimental investigation, cfd and theoretical modeling of two-phase heat transfer in a three-leg multi-channel heat pipe," *International Journal of Heat and Mass Transfer*, vol. 203, p. 123813, 2023. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123813>
- [30] S. Kazi, "Heat transfer-fundamentals, enhancement and applications," p. 290, 2023. [Online]. Available: <https://doi.org/10.5772/intechopen.97951>

- [31] H. Schlichting and K. Gersten, "Boundary-layer theory," *springer*, pp. 1–6, 2016. [Online]. Available: <https://doi.org/10.1007/978-3-662-52919-5>
- [32] O. Reynolds, "Xxix. an experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. philosophical transactions of the royal society of london," *THE ROYAL SOCIETY*, vol. 174, pp. 935–982, 1883. [Online]. Available: <https://doi.org/10.1098/rstl.1883.0029>
- [33] A. Dmitrenko, "Theoretical calculation of the laminar–turbulent transition in the round tube on the basis of stochastic theory of turbulence and equivalence of measures," *Continuum Mechanics and Thermodynamics*, pp. 1–18, 2022. [Online]. Available: <https://doi.org/10.1007/s00161-022-01125-4>
- [34] U. Müller and L. Bühler, "Magnetofluidynamics in channels and containers," *Springer Science Business Media*, 2001. [Online]. Available: <https://doi.org/10.1007/978-3-662-04405-6>
- [35] J. Brill, "Multiphase flow in wells," *Journal of petroleum technology*, vol. 39, no. 01, pp. 15–21, 1987. [Online]. Available: <https://doi.org/10.2118/16242-PA>
- [36] A. Darbyshire and T. Mullin, "Transition to turbulence in constant-mass-flux pipe flow," *Journal of Fluid Mechanics*, vol. 289, no. 2, pp. 83–114, 1995. [Online]. Available: <https://doi.org/10.1017/S0022112095001248>
- [37] M. Hovland, J. Gardner, and A. Judd, "The significance of pockmarks to understanding fluid flow processes and geohazards," *Geofluids*, vol. 2, no. 2, pp. 127–136, 2002. [Online]. Available: <https://doi.org/10.1046/j.1468-8123.2002.00028.x>
- [38] E. Boyd, "Fluid mechanics. vii streeter. mcgraw-hill, 1971. 751 pp.£ 6." *The Aeronautical Journal*, vol. 75, no. 727, pp. 484–484, 1971. [Online]. Available: <https://doi.org/10.1017/S000192400004584X>
- [39] M. Estakharsar and R. Rafee, "Effects of wavelength and number of bends on the performance of zigzag demisters with drainage channels," *Applied Mathematical Modelling*, vol. 40, no. 2, pp. 685–699, 2016. [Online]. Available: <https://doi.org/10.1016/j.apm.2015.08.023>
- [40] F. Beckett, H. Mader, J. Phillips, A. Rust, and F. Witham, "An experimental study of low-reynolds-number exchange flow of two newtonian fluids in a vertical pipe," *Journal of Fluid Mechanics*, vol. 682, no. 2, pp. 652–670., 2011. [Online]. Available: <https://doi.org/10.1017/jfm.2011.264>
- [41] D. McEligot, L. Ormand, H. Perkins, and Jr, "Internal low reynolds-number turbulent and transitional gas flow with heat transfer," *ASME Journal of Heat and Mass Transfer*, vol. 88, no. 2, pp. 239–245, 1966. [Online]. Available: <https://doi.org/10.1115/1.3691521>
- [42] M. Everts and J. Meyer, "Heat transfer of developing and fully developed flow in smooth horizontal tubes in the transitional flow regime," *International Journal of Heat and Mass Transfer*, vol. 117, no. 2, pp. 1331–1351, 2018. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.071>
- [43] A. Metzner and J. Reed, "Flow of non-newtonian fluids—correlation of the laminar, transition, and turbulent-flow regions," *Aiche journal*, vol. 1, no. 4, pp. 434–440, 1955. [Online]. Available: <https://doi.org/10.1002/aic.690010409>
- [44] J. Tu, G. Yeoh, and C. Liu, "Computational fluid dynamics: a practical approach." *Butterworth-Heinemann*, vol. 2, no. 2, pp. 127–136, 2018. [Online]. Available: <https://doi.org/10.1016/C2010-0-67980-6>
- [45] R. Ghidossi, D. Veyret, and P. Moulin, "Computational fluid dynamics applied to membranes: State of the art and opportunities," *Chemical Engineering and Processing: Process Intensification*, vol. 45, no. 6, pp. 437–454, 2006. [Online]. Available: <https://doi.org/10.1016/j.ccep.2005.11.002>
- [46] T. Jankowski, "Minimizing entropy generation in internal flows by adjusting the shape of the cross-section," *International Journal of Heat and Mass Transfer*, vol. 52, no. 15–16, pp. 3439–3445, 2009. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2009.03.016>
- [47] C. Altemani and E. Sparrow, "Turbulent heat transfer and fluid flow in an unsymmetrically heated triangular duct," *International Journal of Heat and Mass Transfer*, vol. 102, no. 4, pp. 590–597, 1980. [Online]. Available: <https://doi.org/10.1115/1.3244357>
- [48] O. Giustolisi, "Using genetic programming to determine chezy resistance coefficient in corrugated channels," *Journal of Hydroinformatics*, vol. 6, no. 3, pp. 157–173, 2004. [Online]. Available: <https://doi.org/10.2166/hydro.2004.0013>
- [49] S. Garimella, "Condensation flow mechanisms in microchannels: basis for pressure drop and heat transfer models," *Heat Transfer Engineering*, pp. 104–116, 2004. [Online]. Available: <https://doi.org/10.1080/01457630490280489>
- [50] S. Kandlikar, D. Schmitt, A. Carrano, and J. Taylor, "Characterization of surface roughness effects on pressure drop in single-phase flow in minichannels," *Physics of Fluids*, vol. 17, no. 10, p. 100606, 2005. [Online]. Available: <https://doi.org/10.1063/1.1896985>
- [51] G. Wang, L. Hao, and P. Cheng, "An experimental and numerical study of forced convection in a microchannel with negligible axial heat conduction," *International Journal of Heat and Mass Transfer*, vol. 52, no. 3–4, pp. 1070–1074, 2009. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2008.06.038>
- [52] A. Okab, H. Hasan, M. Hamzah, K. Egab, A. Al-Manea, and T. Yusaf, "Analysis of heat transfer and fluid flow in a microchannel heat sink with sidewall dimples and fillet profile," *International Journal of Thermofluids*, vol. 15, no. 2, p. 100192, 2022. [Online]. Available: <https://doi.org/10.1016/j.ijft.2022.100192>
- [53] M. Bahrami, M. Yovanovich, and J. Culham, "A novel solution for pressure drop in singly connected microchannels of arbitrary cross-section," *International Journal of Heat and Mass Transfer*, vol. 50, no. 13–14, pp. 2492–2502, 2007. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2006.12.019>
- [54] C. Fung and M. Majnis, "Computational fluid dynamic simulation analysis of effect of microchannel geometry on thermal and hydraulic performances of micro channel heat exchanger," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 62, no. 2, pp. 198–208, 2019. [Online]. Available: <https://doi.org/10.1046/j.1468-8123.2002.00028.x>
- [55] B. Debtera, V. Prabhu Sundramurthy, and I. Neme, "Computational fluid dynamics simulation and analysis of fluid flow in pipe: Effect of fluid viscosity," *Journal of Computational and Theoretical Nanoscience*, vol. 18, no. 3, pp. 805–810, 2021. [Online]. Available: <https://doi.org/10.1166/jctn.2021.9680>
- [56] M. Bahrami, M. Yovanovich, and J. Culham, "January. pressure drop of fully-developed, laminar flow in microchannels of arbitrary cross-section," *In International Conference on Nanochannels, Microchannels, and Minichannels*, vol. 41855, pp. 269–280, 2005. [Online]. Available: <https://doi.org/10.1115/1.2234786>
- [57] M. S. Rawool, A. S. and S. Kandlikar, "Numerical simulation of flow through microchannels with designed roughness," *Microfluidics and nanofluidics*, vol. 2, no. 2, pp. 215–221, 2006. [Online]. Available: <https://doi.org/10.1007/s10404-005-0064-5>
- [58] M. Bahrami, M. Yovanovich, and J. Culham, "Pressure drop of fully developed, laminar flow in rough microtubes," vol. 2, no. 2, pp. 127–136, 2006. [Online]. Available: <https://doi.org/10.1115/1.2175171>
- [59] M. McCormack, F. Fang, and J. Zhang, "Numerical analysis of microchannels designed for heat sinks," *Nanomanufacturing and Metrology*, pp. 1–16, 2021. [Online]. Available: <https://doi.org/10.1007/s41871-021-00118-2>
- [60] P. Parida, "Experimental investigation of heat transfer rate in micro-channels," *Louisiana State University and Agricultural Mechanical College*, vol. 2, pp. 127–136, 2007. [Online]. Available: <https://doi.org/10.31390/gradschool.theses.849>
- [61] M. Akbari, D. Sinton, and M. Bahrami, "Pressure drop in rectangular microchannels as compared with theory based on arbitrary cross section," *Journal of Fluids Engineering*, vol. 131, no. 4, p. 041202 (8 pages), 2009. [Online]. Available: <https://doi.org/10.1115/1.3077143>
- [62] G. Hetsroni, A. Mosyak, E. Pogrebnyak, and L. Yarín, "Heat transfer in micro-channels: Comparison of experiments with theory and numerical results," *International Journal of Heat and Mass Transfer*, vol. 48, no. 25–26, pp. 5580–5601, 2005. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2005.05.041>
- [63] S. Garimella, A. Fleischer, J. Murthy, A. Keshavarzi, R. Prasher, C. Patel, S. Bhavnani, R. Venkatasubramanian, R. Mahajan, Y. Joshi, and B. Sammakia, "Thermal challenges in next-generation electronic systems," *IEEE Transactions on Components and Packaging Technologies*, vol. 31, no. 4, pp. 801–815, 2008. [Online]. Available: <https://doi.org/10.1109/TCAPT.2008.2001197>

- [64] J. Beck, M. Palmer, K. Inman, J. Wohld, M. Cummings, R. Fulmer, B. Scherer, and S. Vafaei, "Heat transfer enhancement in the microscale: Optimization of fluid flow," *Nanomaterials*, vol. 12, no. 20, p. 3628, 2022. [Online]. Available: <https://doi.org/10.3390/nano12203628>
- [65] R. Pryor, "Multiphysics modeling using comsol®: a first principles approach," *Jones Bartlett Publishers*, vol. 2, no. 2, p. 852, 2009. [Online]. Available: <https://doi.org/10.1007/9781439801611>
- [66] S. Nevey, "The ansys fluent package combines deep physics and years of simulation development expertise to solve cfd challenges—right out of the box." [Online]. Available: <https://doi.org/10.1007/9781439801611>
- [67] E. Alawadhi, "book:finite element simulations using ansys crc press," *TaylorFrancis Group*, p. 416, 2014. [Online]. Available: <https://doi.org/10.1201/9781439801611>
- [68] N. Gupta, N. Bhardwaj, G. Khan, and V. Dave, "Global trends of computational fluid dynamics to resolve real world problems in the contemporary era," *Current Biochemical Engineering*, vol. 6, no. 3, pp. 136–155, 2020. [Online]. Available: <https://doi.org/10.2174/2212711906999200601121232>
- [69] X. Xie, L. Zhang, L. Zhu, Y. Li, T. Hong, W. Yang, and X. Shan, "State of the art and perspectives on surface-strengthening process and associated mechanisms by shot peening," *Coatings*, vol. 13, no. 5, p. 859, 2023. [Online]. Available: <https://doi.org/10.3390/coatings13050859>
- [70] Q. Li, G. Yu, S. Liu, and S. Zheng, "Application of computational fluid dynamics and fluid structure interaction techniques for calculating the 3d transient flow of journal bearings coupled with rotor systems," *Chinese Journal of Mechanical Engineering*, vol. 25, no. 5, pp. 926–932, 2012. [Online]. Available: <https://doi.org/10.3901/CJME.2012.05.926>
- [71] B. Debtera, V. Prabhu Sundramurthy, and I. Neme, "Computational fluid dynamics simulation and analysis of fluid flow in pipe: Effect of fluid viscosity," *Journal of Computational and Theoretical Nanoscience*, vol. 18, no. 2021, pp. 805–810, 2021. [Online]. Available: <https://doi.org/10.1166/jctn.2021.9680>
- [72] S. Brunton, J. Proctor, and J. Kutz, "Discovering governing equations from data by sparse identification of nonlinear dynamical systems," *Proceedings of the national academy of sciences*, vol. 113, no. 15, pp. 3932–3937, 2016. [Online]. Available: <https://doi.org/10.1073/pnas.1517384113>
- [73] B. Rozon, "A generalized finite volume discretization method for reservoir simulation," *In SPE Symposium on Reservoir Simulation. OnePetro*, vol. 13, no. 5, p. 859, 1989. [Online]. Available: <https://doi.org/10.2118/18414-MS>
- [74] T. Insperger and G. Stépán, "Updated semi-discretization method for periodic delay-differential equations with discrete delay," *International journal for numerical methods in engineering*, vol. 61, no. 1, pp. 117–141, 2004. [Online]. Available: <https://doi.org/10.1002/nme.1061>
- [75] O. Franke, T. Reilly, and G. Bennett, "Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems: an introduction," *USGS*, no. 5, p. 15p, 1987. [Online]. Available: <https://doi.org/10.3133/twri03B5>
- [76] J. Pegues, S. Shao, N. Shamsaei, N. Sanaei, A. Fatemi, D. Warner, P. Li, and N. Phan, "Fatigue of additive manufactured ti-6al-4v, part i: The effects of powder feedstock, manufacturing, and post-process conditions on the resulting microstructure and defects," *International Journal of Fatigue*, vol. 132, p. 105358, 2020. [Online]. Available: <https://doi.org/10.1016/j.ijfatigue.2019.105358>
- [77] S. Jain, "Open-channel flow," *John Wiley Sons*, 2000. [Online]. Available: <https://doi.org/10.1002/9781119664338>
- [78] G. Moglen, "Fundamentals of open channel flow," *CRC Press*, 2022. [Online]. Available: <https://doi.org/10.1201/9781003263630>
- [79] M. Whitby and N. Quirke, "Fluid flow in carbon nanotubes and nanopipes," *Nature nanotechnology*, vol. 2, no. 2, pp. 87–94, 2007. [Online]. Available: <https://doi.org/10.1038/nnano.2006.175>
- [80] X. Wang, A. Mujumdar, and C. Yap, "Thermal characteristics of tree-shaped microchannel nets for cooling of a rectangular heat sink," *International Journal of Thermal Sciences*, vol. 45, no. 11, pp. 1103–1112, 2006. [Online]. Available: <https://doi.org/10.1016/j.ijthermalsci.2006.01.010>
- [81] S. Lee, "Optimum design and selection of heat sinks," *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A*, vol. 18, no. 4, pp. 812–817, 1995. [Online]. Available: <https://doi.org/10.1109/95.477468>
- [82] T. Al-Hattab, A. Al-Moosawy, and A. Shaker, "Heat transfer calculations of non-developed steady laminar flow between parallel plates," *The Iraqi Journal For Mechanical And Material Engineering*, vol. 8, no. 1, pp. 25–42, 2008. [Online]. Available: <https://doi.org/10.1007/9781439801611>
- [83] M. Hasan, A. Rageb, M. Yaghoubi, and H. Homayoni, "Influence of channel geometry on the performance of a counter flow microchannel heat exchanger," *International Journal of Thermal Sciences*, vol. 48, no. 8, pp. 1607–1618, 2009. [Online]. Available: <https://doi.org/10.1016/j.ijthermalsci.2009.01.004>
- [84] B. Nasir, "Design of micro-hydro-electric power station," *International Journal of Engineering and Advanced Technology*, vol. 2, no. 5, pp. 39–47, 2013. [Online]. Available: <https://www.ijeat.org/wp-content/uploads/papers/v2i5/E1658062513.pdf>
- [85] P. Monadjemi, "General formulation of best hydraulic channel section," *Journal of Irrigation and Drainage Engineering*, vol. 120, no. 1, pp. 27–35, 1994. [Online]. Available: [https://doi.org/10.1061/\(ASCE\)0733-9437\(1994\)120:1\(27\)](https://doi.org/10.1061/(ASCE)0733-9437(1994)120:1(27))
- [86] R. French and R. French, "Open-channel hydraulics (p. 705). new york: Mcgraw-hill., 1985. open-channel hydraulics (p. 705). new york: Mcgraw-hill." no. 5, pp. 39–47, 1985. [Online]. Available: <https://doi.org/10.1007/9781439801611>
- [87] P. Julien and J. Wargadalam, "Alluvial channel geometry: theory and applications," *Journal of Hydraulic Engineering*, vol. 121, no. 4, pp. 312–325, 1995. [Online]. Available: [https://doi.org/10.1061/\(ASCE\)0733-9429\(1995\)121:4\(312\)](https://doi.org/10.1061/(ASCE)0733-9429(1995)121:4(312))
- [88] R. May, "Hydraulic design of side weirs," *Thomas Telford*, no. 5, 2003. [Online]. Available: <https://doi.org/10.1680/hdosw.31678>
- [89] A. Asadollahi, J. Esfahani, and R. Ellahi, "Evacuating liquid coatings from a diffusive oblique fin in micro-/mini-channels: an application of condensation cooling process," *Journal of Thermal Analysis and Calorimetry*, vol. 138, no. 1, pp. 255–263, 2019. [Online]. Available: <https://doi.org/10.1007/s10973-019-08243-3>
- [90] W. Li and Z. Wu, "A general criterion for evaporative heat transfer in micro-/mini-channels," *International Journal of Heat and Mass Transfer*, vol. 53, no. 9–10, pp. 1967–1976, 2010. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2009.12.059>
- [91] M. Hajialibabaei and M. Saghri, "A critical review of the straight and wavy microchannel heat sink and the application in lithium-ion battery thermal management," *International Journal of Thermofluids*, vol. 14, no. 2022, p. 100153, 2022. [Online]. Available: <https://doi.org/10.1016/j.ijft.2022.100153>
- [92] Y. Mu, L. Chen, Y. He, and W. Tao, "Numerical study on temperature uniformity in a novel mini-channel heat sink with different flow field configurations," *International Journal of Heat and Mass Transfer*, vol. 85, pp. 147–157, 2015. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2015.01.093>
- [93] M. Ghorbani, M. Yildiz, D. Gozuacik, and A. Kosar, "Cavitating nozzle flows in micro-and minichannels under the effect of turbulence," *Journal of Mechanical Science and Technology*, vol. 30, no. 5, pp. 2565–2581, 2016. [Online]. Available: <https://doi.org/10.1016/j.jmst.2016.05.010>
- [94] N. Mahmoud, H. Jaffal, and A. Imran, "Performance evaluation of serpentine and multi-channel heat sinks based on energy and exergy analyses," *Applied Thermal Engineering*, vol. 186, no. 5, p. 116475, 2020. [Online]. Available: <https://doi.org/10.1016/j.applthermaleng.2020.116475>
- [95] J. Li, "Computational analysis of nanofluid flow in microchannels with applications to micro-heat sinks and bio-mems," *Coatings*, p. 859, 2008. [Online]. Available: <https://doi.org/10.1007/9781439801611>
- [96] P. Gunasegaran, H. Mohammed, N. Shuaib, and R. Saidur, "The effect of geometrical parameters on heat transfer characteristics of microchannels heat sink with different shapes," *International communications in heat and mass transfer*, vol. 37, no. 8, pp. 1078–1086, 2010. [Online]. Available: <https://doi.org/10.1016/j.icheatmasstransfer.2010.06.014>
- [97] F. Schönfeld and S. Hardt, "Simulation of helical flows in microchannels," *AIChE Journal*, vol. 50, no. 4, pp. 771–778, 2004. [Online]. Available: <https://doi.org/10.1002/aic.10071>
- [98] H. Wang, Z. Chen, and J. Gao, "Influence of geometric parameters on flow and heat transfer performance of micro-channel heat sinks," *Applied Thermal Engineering*, vol. 107, pp. 870–879, 2016. [Online]. Available: <https://doi.org/10.1016/j.applthermaleng.2016.07.039>
- [99] M. Magnini and O. Matar, "Numerical study of the impact of the channel shape on microchannel boiling heat transfer," *International*

- Journal of Heat and Mass Transfer*, vol. 150, p. 119322, 2020. [Online]. Available: <https://doi.org/10.1016/j.jheatmasstransfer.2020.119322>
- [100] D. Jing and L. He, "Numerical studies on the hydraulic and thermal performances of microchannels with different cross-sectional shapes," *International Journal of Heat and Mass Transfer*, vol. 143, no. 5, p. 118604, 2019. [Online]. Available: <https://doi.org/10.1016/j.jheatmasstransfer.2019.118604>
- [101] M. Salimpour, M. Sharifhasan, and E. Shirani, "Constructal optimization of microchannel heat sinks with noncircular cross sections," *Heat Transfer Engineering*, vol. 34, no. 10, pp. 863–874, 2013. [Online]. Available: <https://doi.org/10.1080/01457632.2012.746552>
- [102] D. Sempértegui-Tapia and G. Ribatski, "The effect of the cross-sectional geometry on saturated flow boiling heat transfer in horizontal micro-scale channels," *Experimental Thermal and Fluid Science*, vol. 89, pp. 98–109, 2017. [Online]. Available: <https://doi.org/10.1016/j.expthermflusci.2017.08.001>
- [103] M. Goodarzi, I. Tlili, Z. Tian, and M. Safaei, "Efficiency assessment of using graphene nanoplatelets-silver/water nanofluids in microchannel heat sinks with different cross-sections for electronics cooling," *International Journal of Numerical Methods for Heat Fluid Flow*, vol. 30, no. 1, pp. 347–372, 2019. [Online]. Available: <https://doi.org/10.1108/HFF-12-2018-0730>
- [104] Y. Chen, C. Zhang, M. Shi, and J. Wu, "Three-dimensional numerical simulation of heat and fluid flow in noncircular microchannel heat sinks," *International Communications in Heat and Mass Transfer*, vol. 36, no. 9, pp. 917–920, 2009. [Online]. Available: <https://doi.org/10.1016/j.icheatmasstransfer.2009.06.004>
- [105] S. Yu and T. Ameel, "Slip-flow heat transfer in rectangular microchannels," *International Journal of Heat and Mass Transfer*, vol. 44, no. 22, pp. 4225–4234, 2001. [Online]. Available: [https://doi.org/10.1016/S0017-9310\(01\)00075-8](https://doi.org/10.1016/S0017-9310(01)00075-8)
- [106] F. Montazeri, M. Tavakoli, and M. Salimpour, "Improving thermal performance of rectangular microchannel heat sinks using porous layer: Cfd simulation and optimization," *Journal of Applied Fluid Mechanics*, vol. 16, no. 8, pp. 1574–1586, 2023. [Online]. Available: <https://doi.org/10.47176/jafm.16.08.1745>
- [107] Y. Alihosseini, M. Azaddel, S. Moslemi, M. Mohammadi, A. Pormohammad, M. Targhi, and M. Heyhat, "Effect of liquid cooling on pcr performance with the parametric study of cross-section shapes of microchannels," *Scientific Reports*, vol. 11, no. 1, pp. 1–12, 2021. [Online]. Available: <https://doi.org/10.1038/s41598-021-95446-0>
- [108] A. Agarwal, T. Bandhauer, and S. Garimella, "Measurement and modeling of condensation heat transfer in non-circular microchannels," *International journal of refrigeration*, vol. 33, no. 6, pp. 1169–1179, 2010. [Online]. Available: <https://doi.org/10.1016/j.jrefrig.2009.12.033>
- [109] A. M. Ali, A. Rona, H. T. Kadhim, M. Angelino, and S. Gao, "Thermo-hydraulic performance of a circular microchannel heat sink using swirl flow and nanofluid," *Applied Thermal Engineering*, vol. 191, p. 116817, 2021. [Online]. Available: <https://doi.org/10.1016/j.applthermaleng.2021.116817>
- [110] J. Song, F. Liu, Y. Sui, and D. Jing, "Numerical studies on the hydraulic and thermal performances of trapezoidal microchannel heat sink," *International Journal of Thermal Sciences*, vol. 161, p. 106755, 2021. [Online]. Available: <https://doi.org/10.1016/j.ijthermalsci.2020.106755>
- [111] A. Khan, S. Kim, and K. Kim, "Multi-objective optimization of an inverse trapezoidal-shaped microchannel," *Heat Transfer Engineering*, vol. 37, no. 6, pp. 571–580, 2016. [Online]. Available: <https://doi.org/10.1080/01457632.2015.1060772>
- [112] M. Hasan, A. Rageb, M. Yaghoubi, and H. Homayoni, "Influence of channel geometry on the performance of a counter flow microchannel heat exchanger," *International Journal of Thermal Sciences*, vol. 48, no. 8, pp. 1607–1618, 2009. [Online]. Available: <https://doi.org/10.1016/j.ijthermalsci.2009.01.004>
- [113] M. Shamsi, O. Akbari, A. Marzban, D. Toghraie, and R. Mashayekhi, "Increasing heat transfer of non-newtonian nanofluid in rectangular microchannel with triangular ribs," *Physica E: Low-Dimensional Systems and Nanostructures*, vol. 93, pp. 167–178, 2017. [Online]. Available: <https://doi.org/10.1016/j.physe.2017.06.015>
- [114] G. Liu, B. Zhang, Y. Zhang, and C. Guo, "Modeling of double-layer triangular microchannel heat sink based on thermal resistance network and multivariate structural optimization using firefly algorithm," *Numerical Heat Transfer, Part B: Fundamentals*, vol. 77, no. 5, pp. 417–428, 2020. [Online]. Available: <https://doi.org/10.1080/10407790.2020.1717834>
- [115] H. Sun, H. Fu, L. Yan, H. Ma, Y. Luan, and F. Magagnato, "Numerical investigation of flow and heat transfer in rectangular microchannels with and without semi-elliptical protrusions," *Energies*, vol. 15, no. 13, 2022. [Online]. Available: <https://www.mdpi.com/1996-1073/15/13/4927>
- [116] X. Li, C. Zou, and A. Qi, "Experimental study on the thermo-physical properties of car engine coolant (water/ethylene glycol mixture type) based sic nanofluids," *International Communications in Heat and Mass Transfer*, vol. 77, pp. 159–164, 2016. [Online]. Available: <https://doi.org/10.1016/j.icheatmasstransfer.2016.08.009>
- [117] S. Peyghambarzadeh, S. Hashemabadi, S. Hoseini, and M. Jamnani, "Experimental study of heat transfer enhancement using water/ethylene glycol based nanofluids as a new coolant for car radiators," *International communications in heat and mass transfer*, vol. 38, no. 9, pp. 1283–1290, 2011. [Online]. Available: <https://doi.org/10.1016/j.icheatmasstransfer.2011.07.001>
- [118] D. Mohammad, M. Hasan, and A. Shkarah, "Numerical investigation of the electric double-layer effect on the performance of microchannel heat exchanger at combined electroosmotic and pressure-driven flow," *Al-Qadisiyah Journal for Engineering Sciences*, vol. 14, no. 1, pp. 64–73, 2021. [Online]. Available: <https://doi.org/10.30772/qjes.v14i1.736>
- [119] E. Dede, S. Joshi, and F. Zhou, "Topology optimization, additive layer manufacturing, and experimental testing of an air-cooled heat sink," *Journal of Mechanical Design*, vol. 137, no. 11, 2015. [Online]. Available: <https://doi.org/10.1115/1.4030989>
- [120] Q. Al-Yasiri, M. Szabo, and M. Arıcı, "A review on solar-powered cooling and air-conditioning systems for building applications," *Energy Reports*, vol. 8, pp. 2888–2907, 2022. [Online]. Available: <https://doi.org/10.1016/j.egyr.2022.01.172>
- [121] X. Ye, H. Zhu, Y. Kang, and K. Zhong, "Heating energy consumption of impinging jet ventilation and mixing ventilation in large-height spaces: A comparison study," *Energy and Buildings*, vol. 130, pp. 697–708, 2016. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2016.08.055>
- [122] N. Choubineh, H. Jannesari, and A. Kasaiean, "Experimental study of the effect of using phase change materials on the performance of an air-cooled photovoltaic system," *Renewable and Sustainable Energy Reviews*, vol. 101, pp. 103–111, 2019. [Online]. Available: <https://doi.org/10.1016/j.rser.2018.11.001>
- [123] A. Shrivastava, J. Jose, Y. Borole, R. Saravanakumar, M. Sharifpur, H. Harasi, R. Razak, and A. Afzal, "A study on the effects of forced air-cooling enhancements on a 150 w solar photovoltaic thermal collector for green cities," *Sustainable Energy Technologies and Assessments*, vol. 49, p. 101782, 2022. [Online]. Available: <https://doi.org/10.1016/j.seta.2021.101782>
- [124] S. Rostami, S. Aghakhani, A. Hajatzadeh Pordanjani, M. Afrand, G. Cheraghian, H. Oztop, and M. Shadloo, "A review on the control parameters of natural convection in different shaped cavities with and without nanofluid," *Processes*, vol. 8, no. 9, p. 1011, 2020. [Online]. Available: <https://doi.org/10.3390/pr8091011>
- [125] A. Makki, S. Omer, and H. Sabir, "Advancements in hybrid photovoltaic systems for enhanced solar cells performance," *Renewable and sustainable energy reviews*, vol. 41, no. 5, pp. 658–684, 2015. [Online]. Available: <https://doi.org/10.1016/j.rser.2014.08.069>
- [126] N. Rahbar and J. Esfahani, "Experimental study of a novel portable solar still by utilizing the heatpipe and thermoelectric module," *Desalination*, vol. 284, pp. 55–61, 2012. [Online]. Available: <https://doi.org/10.1016/j.desal.2011.08.036>
- [127] C. Wang, G. Zhang, X. Li, J. Huang, Z. Wang, Y. Lv, L. Meng, W. Situ, and M. Rao, "Experimental examination of large capacity lifepo4 battery pack at high temperature and rapid discharge using novel liquid cooling strategy," *International Journal of Energy Research*, vol. 42, no. 3, pp. 1172–1182, 2018. [Online]. Available: <https://doi.org/10.1002/er.391>
- [128] P. Dhar and S. Singh, "Studies on solid desiccant based hybrid air-conditioning systems," *Applied Thermal Engineering*, vol. 21, no. 2, pp. 119–134, 2001. [Online]. Available: [https://doi.org/10.1016/S1359-4311\(00\)00035-1](https://doi.org/10.1016/S1359-4311(00)00035-1)
- [129] H. Mohsen and N. Hamza, "Investigation of laminar forced convection using a different shape of a heat sink," *Al-Qadisiyah Journal for*

- Engineering Science*, vol. 15, no. 2, pp. 73–79, 2022. [Online]. Available: <https://doi.org/10.30772/qjes.v15i2.816>
- [130] H. Yu, T. Li, X. Zeng, T. He, and N. Mao, “A critical review on geometric improvements for heat transfer augmentation of microchannels,” *Energies*, vol. 15, no. 24, p. 9474, 2022. [Online]. Available: <https://doi.org/10.3390/en15249474>
- [131] A. Ali, M. Hasan, and G. Adnan, “Numerical investigation of roughness effects on hydrodynamic and thermal performance of counter flow microchannel heat exchanger,” *Al-Qadisiyah Journal for Engineering Sciences*, vol. 11, no. 4, pp. 426–445, 2018. [Online]. Available: <https://doi.org/10.30772/qjes.v11i4.571>
- [132] K. Lu, C. Wang, C. Wang, X. Fan, F. Qi, and H. He, “Topological structures for microchannel heat sink applications—a review,” *Manufacturing Review*, vol. 10, 2023. [Online]. Available: <https://doi.org/10.1051/mfreview/2022035>
- [133] Q. Su, S. Chang, M. Song, Y. Zhao, and C. Dang, “An experimental study on the heat transfer performance of a loop heat pipe system with ethanol-water mixture as working fluid for aircraft anti-icing,” *International Journal of Heat and Mass Transfer*, vol. 139, pp. 280–292, 2019. [Online]. Available: <https://doi.org/10.1016/j.ijheatmasstransfer.2019.05.015>
- [134] I. Sarbu and C. Sebarchievici, “Review of solar refrigeration and cooling systems,” *Energy and buildings*, vol. 67, pp. 286–297, 2013. [Online]. Available: <https://doi.org/10.1016/j.enbuild.2013.08.022>
- [135] Z. Gu, H. Liu, and Y. Li, “Thermal energy recovery of air conditioning system—heat recovery system calculation and phase change materials development,” *Applied Thermal Engineering*, vol. 24, no. 17–18, pp. 2511–2526, 2004. [Online]. Available: <https://doi.org/10.1016/j.applthermaleng.2004.03.017>
- [136] A. Boretti, “Analysis of design of pure ethanol engines (no. 2010-01-1453),” *SAE Technical Paper*, vol. 13, no. 5, p. 859, 2010. [Online]. Available: <https://doi.org/10.4271/2010-01-1453>
- [137] M. Preißinger, J. Schwöbel, A. Klamt, and D. Brüggemann, “Multi-criteria evaluation of several million working fluids for waste heat recovery by means of organic rankine cycle in passenger cars and heavy-duty trucks,” *Applied energy*, vol. 206, pp. 887–899, 2017. [Online]. Available: <https://doi.org/10.1016/j.apenergy.2017.08.212>

How to cite this article:

Ghufran Kadhim and Ahmed Al-Saadi. (2025). 'A critical review of forced convection in microchannels', *Al-Qadisiyah Journal for Engineering Sciences*, 18(3), pp. 239-248. <https://doi.org/10.30772/qjes.2023.141506.1003>