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A critical review of forced convection in microchannels

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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 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 has 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.

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/cm^2 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.

Peng and Peterson [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 Choi et al., the word "nanofluids" refers to a brand-new

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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/cm^2 critical heat flow [17]. Green et al. [18] achieved a heat flux of up to 2 kW/cm^2 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]. 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.

Table 1. shows the distinction between minichannels and microchannels.

Type of channel	Hydraulic diameter (*D_H*)
Minichannels	$3\ mm \geq D_H > 200\ \mu m$
Microchannels	$200\ \mu m \geq D_H > 10\ \mu m$

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]. 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.

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 the process of exchanging heat energy between two or more bodies or systems. It is an interdisciplinary subject that includes various fields of research, such as mechanical, chemical, and electrical engineering, materials science, and physics [28]. Researchers in the field of fundamental heat transfer use theoretical, experimental, and computational methods to study the phenomenon of heat transfer [29]. They develop mathematical models, conduct laboratory experiments, and use computer simulations to investigate the mechanisms of heat transfer and optimize thermal management systems. Overall, the field of fundamental heat transfer is crucial in various industrial and technological applications, and its significance is increasing as technology advances and new challenges arise [30].

2.1. Reynolds number

In fluid mechanics, the dimensionless Reynolds number is used to indicate how turbulent or laminar the flow of a fluid is. It is explained as the proportion of inertial to viscous forces in a fluid [31,32]. The formula for Reynolds number is

$$Re = (\rho V D_H)/\mu$$

where μ is the fluid's dynamic viscosity, D_H stands for hydraulic diameter for all types of ducts, V is the velocity of the fluid, and ρ is the density of the fluid.

The flow is regarded as laminar if Re has a value lower than 2300, implying that the fluid particles travel in a predictable and ordered pattern. Re over 4000 is regarded as turbulent, implying that the fluid particles are moving in an erratic and chaotic way. Between 2300 and 4000, the flow may transition between laminar and turbulent depending on changing conditions [33].

2.2. Type of flow

A fascinating phenomenon, fluid flow is important in many engineering and scientific disciplines. The investigation of how liquids or gases move through various media, such as pipes, channels, and ducts, is a key component of the study of fluid flow [34]. Designing and improving systems that carry fluids, such pipelines, pumps, and turbines, requires an understanding of fluid flow. 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, go over its characteristics, and explain 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. Eddies are created as a result, which causes a significant loss of energy [39]. This kind of fluid flow is quantified for pipe flow by a Reynolds number, which is a non-dimensional quantity [40].

Laminar flow is referred to as occurring when the Reynolds number is lower than 2000. The flow is referred to as turbulent if the Reynolds number is greater than 4000. There are two possible flow types when the Reynolds number is between 2000 and 4000: laminar and turbulent. Understanding the many types of fluid flow is crucial in a variety of disciplines, including engineering, science, and medicine [41]. The behavior of fluids under various circumstances is influenced by the diverse properties of laminar flow, turbulent flow, and transitional flow. While turbulent flow is chaotic and unpredictable, laminar flow is smooth and predictable [42]. Laminar and turbulent flow are both present in transitional flow. Each type of flow has pros and cons, and variables like viscosity, density, and velocity can affect how each type of flow behaves [43]. In a variety of applications, including aerodynamics, hydraulics, and blood flow in the human body, properly managing fluid flow is crucial to obtaining maximum efficiency and performance [44]. For optimal efficacy and efficiency, fluid systems can be designed and optimized with an understanding of the many forms of fluid flow. Overall, fluid flow is an intriguing and challenging subject that necessitates a thorough comprehension of the physical characteristics of fluids and their behavior under various conditions [45].

2.3. Hydraulic diameter

Hydraulic diameter is a measure of the effective internal diameter of a conduit or channel carrying a fluid. It is defined as four times the ratio of the cross-sectional area of the conduit or channel to its wetted perimeter [46]. Mathematically, the hydraulic diameter can be expressed as:

$$D_H = 4A/P$$

where D_H is the hydraulic diameter, A is the cross-sectional area of the conduit or channel, and P is the wetted perimeter. The hydraulic diameter is useful for determining the fluid flow characteristics of a conduit or channel, such as its friction factor and Reynolds number [47]. The hydraulic diameter is especially helpful when dealing with non-circular conduits or channels, as it provides an equivalent diameter that can be used in calculations as if the flow were occurring in a circular conduit or channel. For example, the hydraulic diameter of a rectangular channel may be used to calculate the friction factor as if the flow were occurring in a circular pipe of equivalent diameter [48]. Another important use of hydraulic diameter is in heat transfer calculations for different geometries. In such scenarios, the hydraulic diameter is used to calculate the heat transfer coefficient and overall heat transfer rate [49]. In summary, hydraulic diameter is a useful parameter for characterizing fluid flow and heat transfer in conduits or channels of different geometries, providing an equivalent measure of the internal diameter that can simplify calculations and comparisons between different systems [50].

2.4. Governing equations

The energy equation, in addition to the Navier-Stokes equations, have been adopted to calculate the heat transfer process. Calculations of radiation heat transfer in most studies of this field are neglected to simplify the solutions. Continuity, momentum, and energy equations used in this field are listed as follows [62]:

$$\nabla \cdot \left[\rho_l \vec{U}\right] = 0$$

$$\nabla \cdot \left[\rho_l \vec{U}\, \overline{U}\right] = -\nabla P + \nabla \cdot \left[\mu_l \nabla \overline{U}\right]$$

$$\nabla \cdot \left[\rho_l \vec{U}\, T\right] = \nabla \cdot \left[\frac{k_l}{C_{p,l}} \nabla T\right]$$

3. Methods of solution

The methodology of fluid flow inside a microchannel typically involves the use of computational fluid dynamics (CFD) simulations [51-58] or experimental techniques [59,60]. Overall, both CFD simulations and experimental techniques can provide valuable insights into fluid flow inside microchannels. The choice of methodology depends on the specific research question and available resources [61-63].

3.1. Experimental

Experimental techniques for studying fluid flow inside microchannels include velocimetry of microparticles (micro-PIV), tracking velocimetry of microparticles (micro-PTV), and micro-Fluidic Resistance (micro-FR). Micro-PIV and micro-PTV involve the use of microscopic particles suspended in the fluid to visualize the flow patterns of the fluid. Micro-FR is a technique that involves measuring the pressure drop across a microchannel at a known flow rate to determine the flow resistance. Experimental techniques may require specialized equipment and are typically time-consuming and expensive [59,60,64].

3.2. Numerical

CFD simulations involve the use of computer software to model the movement of fluids inside a microchannel. The simulation involves discretizing the fluid domain into small volumes and solving the governing equations of fluid flow using numerical methods. The simulation can be used to predict the velocity, pressure, and other fluid properties at different points within the microchannel. The accuracy of CFD simulations depends on the quality of the model input, including boundary conditions and fluid properties [51-58].

3.2.1. COMSOL software

COMSOL is a powerful software package for modelling and simulating complex physical systems in a wide range of scientific and engineering fields [65]. It allows users to create virtual models of real-world phenomena, such as fluid dynamics, heat transfer, chemical reactions, and electromagnetics, and simulate how these models behave under different conditions. COMSOL is widely used in academia, industry, and research institutions to design and optimize new products and processes, as well as to improve our understanding of the natural world [65]. Some of the key features of COMSOL include its user-friendly interface, extensive library of pre-built model templates, and ability to integrate with other computational tools and software packages [65].

3.2.2. Ansys software

Ansys software is commonly used for numerical simulations in engineering and physics fields. Users can simulate and analyze numerous kinds of physical processes using the finite element analysis software Ansys. [66,67], such as stress and strain, fluid dynamics, heat transfer, electromagnetic fields, and more. Ansys software offers a variety of tools and features to create and manipulate complex models, and its powerful solver technology can accurately simulate real-world scenarios [68]. Ansys has been used in a variety of sectors, including biomedical engineering, aerospace, automotive, and defense [69].

3.2.3. Matlab

MATLAB is a software that is widely used in computational fluid dynamics [70]. It can be used to solve various fluid dynamics problems, including laminar and turbulent flow, heat transfer, and multiphase flow. However, the usage of MATLAB in fluid flow requires in-depth knowledge of the program [71]. The basic steps to using MATLAB in fluid flow simulations are as follows: Define the problem and set up the governing equations [72]. Then, discretize the governing equation(s) using finite difference, finite volume, or finite element techniques [73]. After that, implement the discretized equation(s) in MATLAB code [74]. Then, define the boundary and initial conditions for the problem [75]. The next step is to run the simulation to solve for the fluid flow variable in the entire domain [76].

4. Geometric design of channels

Geometric design of channels is the process of determining the optimal shape and dimensions of a channel for efficient and safe conveyance of water or other fluids [77]. This involves consideration of various factors such as flow rate, sediment transport, erosion, and hydraulic efficiency. An essential aspect of channel design is preventing flooding, protecting infrastructure, and ensuring water sustainability. It requires a solid understanding of fluid mechanics, hydraulic principles, and earthwork construction techniques. Geometric design of channels typically includes determining the channel alignment, cross-section, bed slope, and bank protection measures [78].

4.1. Channels

A channel is typically a long, narrow, and enclosed structure that is used to control the flow of fluids such as water, gas, or oil [79]. The design of the channel is critical to ensuring that the flow is efficient and that there is minimal energy loss due to friction. The geometry design of a channel refers to the shape and dimensions of the channel that is used to on [80]. The first step in designing a channel is to determine the flow rate and the properties of the fluid that will be transported. This includes the viscosity, density, and temperature of the fluid [81,82]. The next step is to determine the dimensions and shape of the channel. The most common shapes of channels are circular, rectangular, and trapezoidal [83]. The shape is determined by the flow rate of the fluid and the terrain that the channel will be installed on [84]. The hydraulic radius is an important factor in channel design. The hydraulic radius is calculated as the ratio of the channel's cross-sectional area to its wetted perimeter [85]. The wetted perimeter is the length of the channel where the fluid makes contact with the sides and bottom of the channel. The hydraulic radius is used to calculate the flow rate and the velocity of the fluid. The slope of the channel is also critical in ensuring efficient flow [86]. The slope, or gradient, is the change in elevation of the channel over a certain distance. The slope of the channel must be steep enough to maintain flow but not too steep that there is excessive erosion or turbulence [87]. Overall, the geometry design of a channel is crucial in ensuring the efficient and safe transportation of fluids. The dimensions, shape, hydraulic radius, and slope must all be carefully considered to ensure that the channel operates as intended and delivers the fluid to its destination with minimal energy loss [88].

4.2. Minichannels

The geometry design of a mini-channel refers to the shape and dimensions of a narrow and compact channel that is used to transport fluids. Mini-channels are typically employed in microfluidic devices for a variety of uses, including chemical analysis, medical diagnosis, and drug delivery [89]. The design of mini-channels is unique and varies significantly from larger channels. The size of the channel is typically less than a millimeter in diameter, which means that the flow properties exhibit different behavior. The fluid flow in mini-channels is laminar, meaning that the fluid flow is streamlined without any turbulence [90]. The geometry of mini-channels may vary depending on the specific application. However, the most common shapes of mini-channels are rectangular and circular. The rectangular cross-section offers more space for functionalization and provides better surface area for heat transfer and chemical reactions [91]. On the other hand, circular channels are easier to fabricate, have low pressure drop, and are more uniform. Mini-channels are typically characterized by their aspect ratio, which is the ratio of the channel's height or width to its length [92]. The aspect ratio is critical in determining the flow properties and pressure drop of mini-channels. Mini-channels with lower aspect ratios tend to have lower pressure drops and are more suitable for microfluidic applications such as lab-on-a-chip devices [93]. Overall, the design of mini-channels is crucial for their effective performance. The shape, size, and aspect ratio of mini-channels must be designed to meet the specific requirements of the intended application and ensure efficient fluid flow and minimal energy loss [94].

4.3. Microchannels

The geometry design of a microchannel refers to the shape and dimensions of a tiny channel or conduit used for fluid transport. Microchannels are used in various applications like microfluidics, chemical processing, and heat transfer applications [95]. The design of a microchannel plays a significant role in determining the fluid flow regime, pressure drop, and heat transfer performance. There are different geometries available for microchannels which are selected based on the application and its requirements [56,96,97]. 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].

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 [106].

4.3.3. Trapezoidal microchannels

Trapezoidal microchannels offer better fluid-dynamics performance than rectangular or circular microchannels [103,104,108,109]. They have a higher thermal exchange capability as they have a larger surface area [110].

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]. The shape also promotes a laminar flow pattern, resulting in reduced pressure drop compared to other microchannel geometries [111]. These channels are commonly used in microfluidic devices for various biomedical applications, such as drug delivery, lab-on-a-chip systems, and cell analysis. The large surface area-to-volume ratio of triangular microchannels provides high fluid pressure drop, efficient mixing, and increased heat transfer rates. Additionally, the triangular shape of the channels allows for higher aspect ratios and increased surface area for chemical or biological reactions. Overall, triangular microchannels offer unique advantages in microfluidic design and have become a popular tool in scientific research and development.

4.3.5. Elliptic microchannels

Elliptic microchannels are a type of microchannel with an elliptical cross-sectional shape. These microchannels offer unique properties that make them suitable for various applications, including microfluidic devices, chemical sensors, and heat exchangers. Elliptic microchannels have a lower pressure drop compared to circular microchannels with the same hydraulic diameter. This is because the hydraulic diameter of an elliptic microchannel is smaller than its geometric diameter, resulting in reduced fluid resistance. Elliptic microchannels have a higher surface-to-volume ratio than circular microchannels, which leads to higher heat transfer rates [100,101].

5. Cooling fluid

Cooling fluid, also known as coolant, is a liquid that is used to transfer heat away from an engine or other machinery component to keep it from overheating. It circulates through a closed system of hoses, pipes, and connections to absorb heat generated by the engine or machinery, and then releases this heat via a radiator or heat exchanger. It also prevents the engine or machinery from freezing in cold temperatures. Different types of cooling fluids are available for different applications, but most are made from a mixture of water and antifreeze or ethylene glycol [112-114].

5.1. Air

Air cooling is a method of dissipating heat from a fluid by using air as the cooling medium. In this process, heat is transferred from the fluid to the air, which then carries the heat away [115]. Air cooling is commonly used in various applications, including automotive engines, electronic devices, industrial processes, and power plants. In these applications, the heated fluid is passed through a heat exchanger, where it is cooled by airflow [116]. The cooled fluid is then circulated back into the system, while the heated air is discharged externally [117]. There are different types of air coolers, including forced-air coolers, natural convection coolers, and hybrid coolers [118]. Forced-air coolers use an external device, such as a fan or blower, to circulate air over the heat exchanger [119]. Natural convection coolers work without any external device and rely on the natural flow of air [120]. Hybrid coolers combine the features of both types and use a fan or blower to enhance natural convection [121]. Air cooling has some advantages over other cooling methods, including low maintenance, lower cost, and portability [122]. However, it also has some limitations, such as lower heat transfer efficiency compared to liquid cooling and reduced performance in high-temperature environments [123]. The effectiveness of air cooling also depends on factors like airflow rate, ambient temperature, and cooling system design [124,125].

5.2. Water

Water in micro-channels has become a highly researched topic in recent years due to its potential applications in various fields, including electronics cooling, chemical and biological analysis, and microfluidic devices [126,127]. With micro-channels, the flow rate of water is significantly reduced, allowing for better efficiency and control of temperature. This property is particularly useful when dealing with small amounts of fluids or biological samples. Water in micro-channels exhibits higher convective heat transfer coefficients than bulk fluids, due to the higher velocity and closer proximity to the channel walls [99,101]. This results in improved cooling capacity, making micro-channels an excellent choice for thermal management in electronics and other applications [104,128]. The use of water in micro-channels has become a popular topic in microfluidics.

5.3. Ethanol

Using ethanol as a cooling fluid is not recommended as it has a low boiling point and may cause risks of flammability and safety hazards. Ethanol is a highly flammable substance that can ignite easily, and it must be handled with particular care [129]. Therefore, it is recommended to use appropriate cooling fluids that are specifically designed for cooling applications [130]. Because ethanol's specific heat capacity is lower than that of other cooling fluids and can only absorb a smaller amount of heat energy per unit mass, using it as a cooling fluid can also be ineffective [131]. This means more quantity of ethanol would be required to cool a given system, making it cost-prohibitive. Also, ethanol is corrosive and can damage some materials commonly used in cooling systems like rubber, plastic, and some metals, leading to leaks and decreased system efficiency [132]. Overall, the use of ethanol as a cooling fluid in industrial applications is not recommended due to safety concerns, low efficiency, and potential for system damage [133].

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.

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Data availability

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

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