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The Effect of Different Surface Shapes (Smooth and Rough Surfaces) on Convection Heat Transfer in Fluids

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Abstract

Surface roughness is one of the factors that inserted can influence fluid behavior, as effective boundary slip can be induced by surface roughness. However, the effect of roughness on this slip remains unclear; effective boundary slip has been found to increase and decrease with increasing roughness A review of the literature indicates a research gap in the absence of studies that have integrated current state variables within a single framework. Therefore, the current research aims to study the effect of different surface shapes—smooth and rough—on convective heat transfer in fluids, focusing on analysis of the relationship between surface properties and heat transfer efficiency. To achieve this goal, the researcher will adopt a descriptive approach, conducting a review of previous relevant studies, with the aim of extracting general patterns, identifying areas of agreement and disagreement in the results, and providing evidence-based scientific recommendations that support the development of practical applications related to heat transfer in industrial and environmental systems.

Keywords: *Smooth surfaces, Rough surfaces, Convection, Heat Transmission, Fluids*

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1. Introduction

Convection heat transfer is one of the most important mechanisms by which thermal energy is exchanged between objects and their surroundings, especially in systems involving fluids. Convection is defined as the process of heat transfer from a solid surface to a fluid or vice versa through fluid movement. Many factors influence the efficiency of this process, including fluid properties, temperature, and flow velocity. However, one factor that has gained increasing attention in recent research is the shape of the surface where heat exchange occurs, particularly the smoothness or roughness of that surface (Mandev & Manay, 2022).

Both traditional and modified or enhanced geothermal systems can benefit from an understanding of the convective heat transfer properties of water in fractures. A thorough understanding of the properties of water flowing through fractures is essential for the creation and use of sustainable geothermal energy. Recent studies have shown that the surface shape of these fractures—whether smooth or rough—can significantly affect the efficiency of heat exchange between the rock and the fluid passing through it (Cernecky, Koniar, & Brodnianska, 2016). This effect is not limited to geothermal energy alone, but extends to a wide range of engineering applications such as industrial chillers, heat exchangers, and nuclear reactor cooling.

In recent years, research has increasingly focused on the use of numerical and experimental modeling techniques to explore the relationship between fluid flow and heat transfer behavior within fractures. For example, Chen and Li (2024)

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revealed that, when compared to smooth surfaces, routing and turbulence in the flow path within rough fractures leads to significant differences in thermal performance. From a different perspective, Dobsakova and Nguyen (2022) examined heat transfer and friction in the context of a single rough rod within a smooth tube. The results were later generalized to more complex systems, highlighting the need for a more precise understanding of the influencing surface factors (Dobsakova & Nguyen, 2022).

Despite these efforts, studies on real rock fractures, which often exhibit natural roughness, remain relatively few. Feyijimi and Fajire (2022) noted a research gap regarding the effect of surface roughness on heat transfer efficiency, particularly in natural and complex environments. Therefore, this research focuses on providing a comprehensive theoretical review of how different surface shapes, whether smooth or rough, affect convection heat transfer in fluids. Its area therefore represents an important starting point for improving the performance of thermal systems in real-world settings, not just in laboratories or idealized models (Feyijimi & Fajire, 2022).

1.1 Research Problem and Questions

Surface properties—whether smooth or rough—are a crucial factor in determining the nature of convective heat transfer, as they affect the behavior of the fluid boundary layer and the efficiency of heat exchange (Demirel, Al-Saud, Al-Ali, & Makkawi, 2019). The comparative influence of natural convection over forced convection increases with the temperature difference in the system and

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decreases with the speed of forced movement. In forced convection, airflow is artificially generated by a fan. The heat transfer coefficient is affected by the temperature, shape, and size of the measured surface, as well as the characteristics of the velocity, temperature, and airflow (Cui & Cui, 2015).

A review of the literature reveals a clear lack of studies examining the effect of surface shape (smooth versus rough) under realistic conditions and in industrial or natural applications. This highlights the need for research that explores this relationship more systematically and comprehensively. Accordingly, this research seeks to answer the following main question: "What is the effect of different surface shapes (smooth and rough) on convective heat transfer in fluids?"

This main question leads to the following sub-questions:

1. To what extent do smooth surfaces affect the rate of convective heat transfer in fluids?
2. How do rough surfaces affect the efficiency of heat transfer in convective systems?
3. What factors control the effectiveness of a surface (texture, distribution, size) in enhancing or reducing heat exchange in fluids?

1.2 Research Aim and Objectives

The current research aims “to investigate the effect of different surface shapes (smooth and rough surfaces) on convection heat transfer in fluids”.

The main aim is divided into the following sub-objectives:

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1. To investigate the effect of smooth surfaces on convection heat transfer in fluids.
2. To investigate the effect of rough surfaces on convection heat transfer in fluids.

1.3 Research Significance

- This research is significant because it is the first to examine the effect of different surface shapes (smooth and rough surfaces) on convection heat transfer in fluids.
- The study creates a conceptual framework for the research independent variable (convection heat transfer in fluids) and dependent variables (smooth and rough surfaces).
- It delivers practical results that might influence the worldwide community, including academic websites, international libraries, and policymakers.
- It helps to address a clear gap in the literature related to the effect of surface nature on the performance of thermal systems, especially in cases of natural convection and forced convection.
- The results are expected to help engineers and designers to select surface types in industrial applications to improve heat transfer efficiency.
- The study serves as a scientific reference that can be used in universities, research centers, and scientific libraries, whether for future research or educational curricula.

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- It paves the way for more detailed or experimental studies focusing on other factors affecting heat transfer, such as fluid quality, temperature, or micro surface treatment.

2. Methodology

The researcher will use the descriptive approach to investigate the goals by reviewing related previous studies that have the same variables. This approach was chosen due to its suitability to the nature of the topic, which focuses on analyzing and interpreting the phenomenon based on available previous scientific studies without conducting direct experiments or collecting field data. The descriptive approach in this study looks at relevant literature and previous studies which address the main variables: surface type (smooth or rough) and the mechanism of convective heat transfer in fluids. Through this analysis, the researcher seeks to understand the nature of the relationship between these variables and review the most prominent findings of previous research in similar contexts.

In order to apply the descriptive approach in a systematic and organized manner, the researcher will rely on several key steps to ensure the study's objectives are achieved accurately and objectively. The first will compile previous studies related to the topic, with a particular focus on research that compared smooth and rough surfaces in the context of convective heat transfer. This is to ensure a comprehensive approach and balance between various research trends. Next, the results of these studies will be analyzed and summarized in terms of measurement methodologies, experimental conditions, fluid type used, surface

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nature, and heat transfer behavior, contributing to a deeper understanding of the phenomenon.

The researcher will also categorize the studies according to surface type and the nature of the heat flow (natural or forced convection), enabling accurate comparisons between different cases and the extraction of credible scientific implications. Through this comparative analysis, general trends and common findings between the studies will be identified, helping to build a comprehensive and integrated understanding of the effect of surface roughness or smoothness on heat transfer efficiency. Finally, the researcher will identify shortcomings or discrepancies in previous results, discussing possible reasons for these discrepancies, such as different testing environments or varying fluid properties. This will open the way for more accurate and comprehensive future research recommendations.

3. Literature Review

3.1 Convection Heat Transfer in Fluids

Convection heat transfer arises from fluid motion, which may be either forced (induced by external devices like pumps or fans) or natural (driven by buoyancy forces due to temperature-induced density differences). This mechanism is central to numerous engineering and industrial applications, including heating and cooling systems, internal combustion engine thermal management, and heat exchangers (Luo et al., 2019).

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In fluids, convection heat transfer depends largely on the properties of the fluid itself (such as viscosity, specific heat, and thermal conductivity), flow conditions (such as flow velocity and flow type: uniform or turbulent), and the geometric properties of the surface in contact with the fluid. Heat transfer rate is usually measured using the Nusselt number (Nu), which is an indicator of the efficiency of convection heat transfer compared to pure thermal conduction.

Experimental and numerical studies have highlighted the sensitivity of convective heat transfer to environmental and surface-related factors, including surface roughness, thermal gradients, and the internal configuration of channels or pipes. For instance, introducing roughness to a surface can intensify turbulence and mixing within the boundary layer, thereby enhancing heat transfer performance— a technique known as thermal enhancement (Zhuang, Huang, & Jiang, 2024).

Convective flows are prevalent in a wide range of industrial and geophysical settings. Their impact extends to critical societal challenges in energy and the environment in the 21st century (Lips & Meyer, 2017). Notable examples include thermal transport in rivers, sea water, and the atmosphere, which are affected by thermal discharges or natural stratification processes. Likewise, energy systems—such as nuclear reactors, solar thermal plants, and urban district heating networks—rely heavily on effective convective transport. Fluids are also extensively employed in industry to regulate temperature in systems like heat exchangers and in electronic components (Rhakasywi & Harinaldi, 2015).

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A heat transmission method known as convection occurs in a fluid as a result of a combination of energy transport from the fluid's macroscopic (bulk) motion and conduction via molecular contacts. The fluid must move in the aforementioned definition, otherwise the heat transmission process degenerates into a static conduction scenario (Yousaf & Usman, 2015). The term "convection" typically requires the presence of a solid surface adjacent to the fluid. Convection can also occur when only fluids are present, as in the situation of a hot jet entering a cool reservoir. Nonetheless, the majority of industrial applications entail a hot or cold surface that either transfers or receives heat from the fluid (Zohuri, 2017).

In the field of microfluidics, fluid flow and heat transfer behavior are profoundly influenced by surface characteristics. Microfluidics has gained considerable attention due to its application across biotechnology, electronics cooling, and chemical processing (Bahrami, 2019). Research has shown that surface wettability plays a pivotal role in microflow dynamics, with rough surfaces containing microstructures that are capable of enhancing hydrophobicity. Surfaces patterned with micrometer-scale pits can repel water efficiently, increasing the contact angle to 160°. This should be contrasted with more conventional methods of increasing the contact angle, like chemical changes and surface coatings, where it is challenging to reach an angle greater than 120° (Pan, 2018; Dobsakova & Nguyen, 2022).

When a moving fluid makes contact with a fixed surface, heat transfer by convection takes place. Heat is carried by the moving fluid and is either drawn out of or deposited on the surface. There are two varieties of convection. In forced

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convection, a mechanism other than surface temperature gradients is drives or forces the fluid forward. The fluid is transported by thermal gradients or surface temperature differences in free convection (Luo, Xu, & Lei, 2019). Convection obeys Newton's law of cooling given by:

$$Q = hA(T_\infty - T_w) \quad \rightarrow (1)$$

$$q = h(T_\infty - T_w) \quad \rightarrow (2)$$

In this instance, q is the heat flux at the wall per unit area. The film heat transfer coefficient, denoted by *h* (or whatever symbol you're using), has units of Btu/h·ft²·°R or W/m²·K. For the majority of materials and flow scenarios, several correlations have been identified for determining an acceptable value of h. The temperature of the fluid distant from the wall during the free-stream condition is T1, and Tw is the wall temperature in equation 1 and 2.

The process by which heat moves through a fluid when bulk fluid motion is present is called convection. Depending on how the fluid motion is started, convection is divided into two categories: forced convection and natural (or free) convection (Ventola, 2014). Any fluid motion in natural convection is brought about by natural processes like the buoyancy effect, which causes the warmer fluid to rise and the cooler fluid to fall. In contrast, forced convection involves using an external device, such as a pump or fan, to push the fluid to flow over a surface or through a tube. Convection heat transfer is challenging because it incorporates both

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heat conduction and fluid motion. Heat transfer is improved by fluid motion; the higher the velocity, the higher the rate of heat transfer (Yousaf & Usman, 2015). The rate of convection heat transfer is expressed by Newton's law of cooling:

$$q''_{conv} = h(T_s - T_\infty) \quad \rightarrow ({}^{W}/_{m^2})$$

$$Q'_{conv} = hA(T_s - T_\infty) \quad \rightarrow (W)$$

In microfluidic systems, where the surface-to-volume ratio is significantly high, conventional no-slip boundary conditions may not hold. Instead, boundary slip can occur, wherein the fluid exhibits a relative velocity relative to the adjacent solid surface. Surface characteristics such as roughness and wettability have been shown to strongly influence this behavior, affecting both momentum and thermal transport at the microscale (Lips & Meyer, 2017).

3.2 The Effect of Smooth Surfaces on Convection Heat Transfer in Fluids

Smooth surfaces are an essential element in the design of many traditional thermal devices, such as heat exchangers and condensers, due to their provision of uniform flow and reduced flow resistance and pressure loss. In convective heat transfer systems, surface smoothness contributes to maintenance of laminar flow, reducing wall-fluid friction and thus reducing energy consumption associated with fluid pumping. However, this reduction in friction comes at the expense of heat transfer efficiency, as uniform fluid flow over smooth surfaces does not generate sufficient turbulence to promote thermal layer mixing, resulting in a lower heat transfer coefficient compared to that of rough surfaces. Studies show that the

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thermal performance of smooth pipes is significantly affected by the temperature gradient coefficient between the wall and fluid, as well as by physical properties of the fluid such as viscosity, density, and specific heat (Yinfei, 2019).

The effectiveness of smooth surfaces is also enhanced in applications that require reduced maintenance costs and reduced deposit buildup or corrosion, such as precision cooling systems or condenser applications in chemical and medical systems. In some advanced applications, the thermal performance of such surfaces may be enhanced using nano-coatings or micro-surface treatments that increase thermal conductivity or change the contact angle without compromising the surface smoothness (Menni et al., 2019).

The equation for heat transfer rate $\dot{Q}$ is one of the basic equations in the theory of heat transfer. The amount of heat $\dot{Q}$ that an object absorbs or radiates to its surroundings over a time unit τ is expressed by this equation. The quantity of thermal energy that an object can hold inside itself is denoted by the heat Q. The object's mass (m), specific heat coefficient (c), and current temperature (t), in degrees Celsius, provide the heat (Lips & Meyer, 2017).

$$Q^{\cdot} = \frac{dQ}{d\tau} = mc\frac{dt}{d\tau}$$

Convection and radiation are two physically distinct processes that transport heat simultaneously. Thus, the convective heat transfer rate Qc and the radiant heat flux Q_r add up to the overall heat transfer rate:

$$Q^{\cdot} = Q_c^{\cdot} + Q_r^{\cdot}$$

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Numerous industrial applications, including those in the automotive, chemical, refrigeration, and air conditioning sectors, involve convective condensation. In these applications, increasing the condenser efficiency reduces the refrigerant load and saves material and space (Yousaf & Usman, 2015). The increased efficiency of these systems also lowers their operating costs and environmental impact. Numerous studies and reviews have already been conducted of convective condensation in horizontal smooth and improved tubes. These studies indicate that pipe performance can be improved by introducing geometric changes to the inner surface, such as adding microgrooves or fins, or using special coatings to increase the effective surface area and enhance condensate drainage. Modifying the pipe angle also contributes to improving the condensation process, with angles between 30° and 45° found to achieve the best performance in terms of increasing heat transfer coefficients. In such systems, the condensed liquid flows downward by gravity, while the vapor rises upward, enhancing heat transfer efficiency (Yinfei, 2019). Thus, smooth surfaces offer a suitable engineering solution in situations where a balance between thermal efficiency, energy consumption, and operational costs is needed, particularly in systems that rely on laminar flow or require stable, homogeneous flow.

3.3 The Effect of Rough Surfaces on Convection Heat Transfer in Fluids

Surface roughness is a major factor affecting convective heat transfer, especially in transitional and turbulent flow systems. In thermal systems, such as heat exchangers, rough surfaces can significantly increase the heat transfer rate by

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creating turbulence in the boundary layer, enhancing turbulence, and improving fluid mixing.

Rough surfaces are typically designed using elements such as ribs, protrusions, or microcavities to improve heat transfer performance by enhancing turbulence in the near-wall flow layer. According to Perry et al. (1987), roughness can be classified into two main types: type d, where the flow cannot penetrate the air bubble inside the cavity, and type k, which allows the flow to penetrate the bubble and Reattach what to the wall surface. The type of roughness depends on the slope-to-height ratio of the rough element (Jiménez, 2004); the higher this ratio, the closer the roughness behavior is to the characteristic roughness of sand grains.

On the other hand, experimental results also showed that roughness leads to a rapid deterioration in flow velocity, which is associated with a rapid increase in boundary layer thickness. In this context, Chakroun et al. (2008) noted that the mean velocity distribution over smooth surfaces exhibit a steeper gradient near the wall than over rough surfaces. In contrast, results obtained by Caliskan and Baskaya (2012) showed that the radial velocity resulting from collisions of a circular jet array on a surface with rough V-shaped elements was higher than in the smooth case at H/D = 3 and with Reynolds number Re = 10000. However, this difference in velocities almost disappears at H/D = 12, where the radial velocities become close at the same locations (Huang et al., 2021).

Heat exchangers and other thermal equipment have many uses in both the home and business sectors. A well-designed heat exchanger should take into

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account ways to simultaneously deal with the pressure drop problem and improve heat transfer performance. All heat exchanger designers face the unavoidable issue that a considerable loss of pressure typically occurs while trying to improve heat transfer performance. As a result, engineers generally build heat exchangers to function using either a laminar or turbulent flow regime rather than the transitional regime due to the latter's alleged uncontrollable behavior. Furthermore, for the transitional flow regime, it is impossible to forecast how heat transmission will change with mass flow rate (Almesri, Alrahmani, Almutairi, & Abou-Ziyan, 2021).

Operation via a transitional flow regime provides an ideal balance between the high heat transfer coefficients of turbulent flow and the low-pressure losses associated with laminar flow. However, this regime is inherently unstable and difficult to predict. Many conventional designs avoid it, preferring more predictable systems despite the potential for increased energy consumption (Tummers & Steunebrink, 2019).

Researchers have explored various roughening techniques, such as spiral-finned tubes and twisted ribbons, to improve thermal performance. These techniques allow engineers to reduce the required flow rate while maintaining or improving heat transfer efficiency, ultimately leading to reduced energy consumption in pumps and compressors (Ventola, 2014). However, experimental data on heat transfer in the transitional regime, especially with internal roughness, are still limited, so to properly examine the effect of surface roughness on the transitional flow regime, new techniques for roughening the inner surface of the tube should be explored (Rhakasywi & Harinaldi, 2015).

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When a fluid passes through a pipe, friction losses will occur. A parameter known as the Darcy-Weisbach friction factor, f, is established in order to express this frictional loss, and is defined by

$$\Delta p = f(L/D_h)\frac{\rho u_{av}^2}{2}$$

Where Δp is the head loss along a pipe length L.The head loss is caused by the wall shear stress τw,

$$\tau_w = \frac{frictional\ force\ on\ liquid}{surface\ area\ of\ pipe} = \frac{\Delta p[(\pi/4)D_h^2]}{\pi D_h L} = \frac{\Delta p D_h}{4L}$$

So the friction factor f can also be expressed as

$$f = \frac{\tau_w}{\rho u_{av}^2/8}$$

The boundary layer (BL) is the thin layer of fluid adjacent to a solid surface, where the fluid velocity gradually changes from zero at the surface to the free velocity of the fluid away from the surface. It plays an important role in resisting fluid flow. Roughness components may disrupt the BL and alter the resistance behaviors of pipes with rough surfaces. The sand grain size, commonly known as the sand grain roughness, is represented here by the letters ks. The definition of the Reynolds number is

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$$Re_8 = \frac{k_8 u^*}{\nu} = Re_{Dh} \frac{k_8}{D_h} \sqrt{\frac{f}{8}}$$

3.4 Related Previous Studies

Cernecky, Koniar, and Brodnianska (2016) investigated the effect of organizing elements for convective heat transfer along shaped heat exchange surfaces. The study examined local heat transfer coefficients at various dimensionless distances (x/s = 0, 0.33, 0.66, and 1). Their findings demonstrated that the incorporation of regulating structures could significantly enhance localized heat transfer performance. Experimental measurements of temperature distribution near the heat exchange surfaces were obtained using holographic interferometry, and the results showed strong agreement with computational fluid dynamics (CFD) simulations in predicting local heat transfer coefficients (α_x).

Rhakasywi and Harinaldi (2016) explored the effect of orifice shape on the convective heat transfer of an impingement jet. The synthetic jet was driven by piezoelectric membranes generating sinusoidal oscillations using a 5-volt electric input. Two orifice configurations—square and circular—were compared. The results indicated that orifice shape, in combination with oscillation frequency, had a substantial impact on cooling efficiency. Specifically, the square orifice produced a greater reduction in surface temperature than the circular one, highlighting the importance of geometrical design in thermal management systems.

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Cui and Cui (2015) conducted a numerical study on the effect of surface wettability and roughness on heat transfer in microchannels. Using a double-distribution-function thermal lattice Boltzmann model, they simulated the transient behavior of hot liquid flow within microchannels featuring diverse surface textures and wetting properties. The results revealed that surface roughness consistently improved heat transfer efficiency, regardless of wettability conditions. In particular, for superhydrophobic smooth surfaces, a gas film formed at the interface acted as a thermal insulator due to the low thermal conductivity of the gas, which significantly influenced heat exchange dynamics.

Luo et al. (2019) carried out an experimental study of heat transfer by water flowing through smooth and rough rock fractures. Parameters such as flow velocity, fluid inlet and outlet temperatures, and surface temperatures were monitored to compute the heat transfer coefficients. The analysis indicated that fracture roughness played a significant role in altering heat transfer behavior, with rougher surfaces promoting more efficient thermal exchange due to increased turbulence and surface area.

Furthermore, Zhuang (2024) examined the effect of volumetric flow rate on heat transfer within fractured rocks exhibiting different surface morphologies and external temperatures. Using 3D numerical simulations in COMSOL Multiphysics, the fluid flow and heat transfer through 3D fracture models characterized by different roughness and apertures were simulated with volumetric flow rates ranging from $1 \times 10{-}6$ m3/s to $1 \times 10{-}5$ m3/s. The results showed that flow rate

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was the dominant factor affecting thermal performance, followed by surface texture and ambient temperature. Higher flow rates not only enhanced heat extraction but also introduced thermal non-uniformities, thereby affecting efficiency. Surface roughness was found to cause uneven temperature distributions, especially in narrow fractures, further influencing heat transfer characteristics.

Lips and Meyer (2017) investigated convective condensation of refrigerant R134a within an inclined smooth tube of 8.38 mm internal diameter. Part I of this experimental study focused on the effect of tube inclination on flow patterns and heat transfer coefficients for various mass fluxes and vapor qualities. Results indicated that for low mass fluxes and vapor qualities, flow behavior was highly sensitive to inclination angles. However, annular flow patterns were observed consistently at higher mass fluxes, regardless of the tube orientation. The findings were benchmarked against existing flow pattern maps, contributing to a better understanding of condensation heat transfer in inclined geometries.

Mandev and Manai (2022) conducted a study to examine the effect of surface roughness in multi-path microchannels on mixed convective heat transfer, where forced and natural convection interact.

The research targeted applications demanding high thermal efficiency, such as the precise thermal management of electronic components. Miniature heat sinks embedded in microchannels exhibiting varying roughness configurations were utilized in the experiments. Both experimental and computational analyses were performed across a broad range of Reynolds and Grashof numbers to accurately

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capture the combined convection effects. The thermal performance was assessed using the Nusselt number as a primary metric, revealing enhanced heat transfer in microchannels with uniformly rough surfaces when compared to smooth ones.

The results showed that the presence of systematically distributed surface roughness within the microchannels led to a significant improvement in heat transfer. Surface changes contributed to enhanced thermal boundary layer turbulence, significantly increasing the Nusselt number under mixed-load conditions. The extent of this improvement was found to be highly dependent on the roughness pattern and distribution, as well as geometric properties of the microchannel, such as width and height. The study concluded that the use of carefully designed surface roughness elements can help to improve the cooling performance of microsystems, especially when using conventional fluids such as water. The researchers highlighted the importance of taking surface roughness into account in future heat sink designs, especially in applications that require high thermal efficiency in a limited space.

Shishkina and Wagner (2011) performed a numerical study using two-dimensional simulations for cases involving a limited number of rectangular roughness elements with relatively large dimensions. The results showed a significant increase in the Nusselt number (Nu). In a subsequent study based on direct numerical simulation (DNS), Wagner and Shishkina (2013) showed that the degree of heat transfer improvement depends on the micro-geometric properties of the roughness elements, such as their shape, size, and positions or spacing between

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them.. The study also indicated that as the Rayleigh number (Ra) increases, the Nusselt number tends to approach those recorded for smooth walls, indicating that, under severe convective conditions, the effect of roughness is reduced.

In another study, Zhou et al. (2016) performed direct numerical simulations of Taylor-Couette flow in the presence of grooved walls. They demonstrated that the relationship between the non-dimensional torque (analogous to the Nusselt number in convective systems) and the Taylor number (analogous to the Rayleigh number) was subject to three distinct regimes. These regimes depend on whether the thickness of the boundary layer generated by the flow (related to the Taylor number) is greater or less than the height of the grooves, indicating that the effect of roughness is directly related to the laminar properties of the flow. The study focuses on the effect of uniform, thermally conductive surface roughness on the flow behavior and heat transfer within cubic Rayleigh-Bénard (R-B) convection cells. It aims to investigate the relationship between the Nusselt number and the Rayleigh number (Nu–Ra) in the presence of rough surfaces, and to determine whether specific physical mechanisms occur within these cells that help to improve heat transfer efficiency. To achieve this goal, two smooth cells and three rough cubic cells were designed, with varying ratios of rough element height to cell height. Two different heights were also chosen for the smooth cells to expand the range of Rayleigh number values covered by the study.

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4. Conclusion

In conclusion, the study results indicate that one of the most important factors affecting heat transfer is water flow velocity, which is followed by rock surface temperature and fracture surface form. Within a particular range, an increase in flow rate significantly improves heat transmission and increases total heat extraction. Temperature non-uniformity is made worse by higher volumetric flow rates, which increase the temperature differential and boost heat transfer effectiveness. To guarantee the most effective heat extraction, fluid parameters must be carefully chosen based on the actual conditions when designing geothermal extraction projects.

In narrower cracks where water–rock heat exchange is intensified, surface roughness significantly affects temperature distribution and produces heterogeneous thermal profiles. This demonstrates how important fracture morphology is to heat transmission properties. In addition, the roughness of the fracture surfaces allows the temperature to drop, which lowers the output temperatures. The longer flow routes and larger heat transfer area due to the surface imperfections are responsible for this phenomenon.

Therefore, the study confirms that selecting the appropriate physical and hydraulic properties of the fluids used is critical to achieving the highest thermal efficiency, especially when designing geothermal energy extraction projects or industrial heat exchange systems. The study recommends that surface characteristics (such as roughness, slope, and actual contact area) should be

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considered in the engineering design of these systems to ensure maximum utilization of the available thermal energy.

The results also indicate the importance of conducting further experimental studies and accurate numerical modeling to understand the combined effect of flow rate, surface nature, and the fluid used, especially in complex or heterogeneous environmental contexts. This study paves the way for the development of improved design strategies based on accurate surface properties and actual flow data, contributing to increased efficiency of thermal energy systems and enhanced reliance on renewable energy sources.

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