Review Article

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Exploring the impact of parameters on flow boiling heat transfer in microchannels and coated microtubes: A comprehensive review

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Abstract: The aim of this study is to present a comprehensive review of the impact of various parameters on flow boiling heat transfer in microchannels and coated microtubes. The objectives of this study are to analyze the existing literature, identify the research methods employed, summarize the findings, and highlight the novelty and potential improvements in the field of microscale heat transfer. The review encompasses a wide range of parameters including fluid flow rate, wall heat flux, surface roughness, tube diameter, and tube coating. By examining these parameters, the study investigates their effects on the heat transfer performance in microchannels and coated microtubes. A systematic analysis is conducted to understand the relationships between these parameters and the heat transfer characteristics. The findings of this review contribute to the current state of knowledge in microscale heat transfer. The analysis reveals significant insights into the impact of various parameters on flow boiling heat transfer, providing valuable information for researchers and engineers in fields such as microelectronics cooling, energy conversion, and biomedical engineering. Moreover, this review identifies areas for further investigation and highlights the challenges and opportunities that lie ahead in this research domain. The novelty and improvement of this work lie in its comprehensive analysis of the interplay between different parameters and their effects on flow boiling heat transfer. By synthesizing the existing literature, this review serves as a valuable resource for researchers and engineers working on microscale heat transfer. It offers a deeper understanding of the subject matter and paves the way for future advancements in the design and optimization of microchannels and coated microtubes for enhanced heat transfer performance.

Keywords: microchannels, flow boiling, heat transfer, coated microtubes, instability, heat flux, mass flux degree of subcooling

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1 Introduction

Flow boiling heat transfer in microchannels and coated microtubes has garnered significant interest in recent years due to its widespread applications in various fields, including electronics cooling, chemical processing, and energy conversion systems. The efficient transfer of heat in such systems is critical to ensure optimal performance and prevent equipment failure.

The understanding of the complex heat transfer phenomena in microchannels and coated microtubes is crucial for designing effective heat transfer systems. Several parameters, such as instability, heat flux, mass flux, and degree of subcooling, have been reported to significantly affect flow boiling heat transfer in microchannels and coated microtubes. Therefore, a comprehensive review of the impact of these parameters on flow boiling heat transfer is necessary.

The aim of this review is to provide a comprehensive overview of the effect of various parameters on flow boiling heat transfer in microchannels and coated microtubes. The review will cover the latest research on the subject, including experimental and numerical studies, and identify the critical parameters that influence flow boiling heat transfer in microchannels and coated microtubes.

Overall, this review will serve as a valuable resource for researchers and engineers in the field of microscale heat transfer, providing a better understanding of the underlying mechanisms and critical parameters that affect flow boiling heat transfer in microchannels and coated microtubes. Microchannel heat exchangers have the potential to achieve very high heat transfer rates compared to traditional heat exchangers because of the extremely high surface area-to-volume ratio. Hence, according to Kandlikar [1], heat dissipation can reach about 10 MW/m^2 when using single-phase flow in microchannels. Unfortunately, this is accompanied by an extreme pressure drop and an uneven temperature distribution. In considering this, an increased amount of investigation has been focused over the course of the past 20 years on the study of flow boiling in microchannel heat exchangers with the intention of cooling high heat flux systems such as electronic devices, laser diodes, isolated gate bipolar transistors, and fuel cell systems. The main benefits of applying flow boiling in these systems can be summarized in the following manner: 1. The surface temperature can be slightly altered by flow boiling. Because of the decreased thermo-mechanical stresses within the chip, this can considerably increase the durability of electronic equipment. 2. A small liquid pump is necessary, resulting in a highly compact cooling system that can be used at a lower cost. Notwithstanding the benefits of flow boiling in microchannel heat sinks, there are still several important problems that are not fully understood. The following are some of the problems: 1. The challenge of initiating boiling, *i.e.*, the need for very high wall superheat at the boiling incipient. 2. Early dry out (low critical heat flux). 3. Flow instabilities and reversals. 4. The boiling characteristics of microchannel flow are not clear. For the reasons stated above, this chapter presents a critical analysis of studying flow boiling in a plain microchannel and enhancing flow boiling in a microchannel with a coating technique on its surface [2].

2 Flow boiling in plain microchannel

2.1 Parameters effect on flow boiling characteristic

Various factors affect flow boiling characteristics, such as fluid, inlet subcooling, mass flux, and heat flux, making it a challenge to predict flow boiling heat transfer.

2.1.1 Rates of heat transfer

2.1.1.1 Inlet subcooling

Some previous studies suggest that subcooling has a negligible impact on heat transfer rates, especially in the saturated boiling area, such as Liu and Garimella, [3]. They studied experimentally the water flow boiling in copper microchannels with subcooling degrees of 5–33 K. It was found that the inlet subcooling affects the onset of nucleate boiling, increasing the degree of subcooling leads to delayed onset of boiling but had negligible influence on the two-phase boiling region. Agostini *et al.* [4] found that at subcooling rate of 0.6–18.3 and 0–19 K of refrigerants R245fa and R236fa, respectively, increasing inlet subcooling had no appreciable impact on heat transfer coefficients (HTCs) in the saturated zone. Additionally, the authors confirm that as inlet subcooling is increased, the HTCs for both fluids decrease in the subcooled region. Likewise, Ong and Thome, [5] examined the effect of intake subcooling at temperatures ranging from 2 to 9 K on the flow boiling temperature of the refrigerants R134a, R245fa, and R236a in circular tubes throughout the microscale range. Reserchers noted a negligible subcooling's impact on the local HTCs at vapor quality $x < 0.1$, which was where boiling incipiency is located has an impact, as discussed above. The same group, Huang and Thome [6], experimentally studied subcooled and saturated flow boiling heat transfer at three inlet subcooling temperatures in multi-microchannel evaporators using refrigerants R245fa and R236fa as working fluid. The experimental results revealed different trends along the flow direction. At the beginning of the channel, the local HTC exhibited decreasing trend due to the single-phase thermal developing flow, and then heat transfer increased from the onset of subcooled flow boiling up until the onset of saturated flow boiling, where it decreased again. Also, results show that at a fixed location along the microchannel, due to a comparable enlargement of a subcooled zone for refrigerants R236fa and R245fa, a local HTC is lower in saturated and subcooled boiling section with increased inlet subcooling. Lee and Karayiannis [7] studied experimentally the influence of inlet subcooling on the flow boiling heat transfer in multi-microchannel using HFE-7200 as a working fluid. The experimental results show that the HTC decreases with the increase in the subcooling degree. The effect of inlet subcooling on the flow boiling heat transfer of deionized (DI) water in a horizontal single microchannel of a square cross-section has been studied by Korniliou and Karayiannis [8]. Authors reported that for given heat flux and mass flux, a decrease in subcooling led to an increase in the HTC. Similarly, Al-Nakeeb *et al.* [9] experimented with a single rectangular microchannel to investigate the effects of degree of inlet subcooling on the flow boiling heat transfer using water as a working fluid. Resercher found that decreasing HTC values with increasing inlet degree of sub-cooled.

Contrary to what was stated above, Huang *et al.* [10] studied the improved or structured microchannel heat sinks and concluded that subcooling had a favorable impact on HTCs. They experimentally studied the effect of inlet subcooling on the local heat transfer in multi-microchannel evaporators using a refrigerant R1233zd(E) as a working fluid. The results shown that a sharp rise in HTC in the subcooled region, which peaks in the region of boiling incipience. This sharp rise is also an indication of enhanced subcooled flow boiling. After the rise, the HTC goes on decreasing along the channel length as the vapor quality increases. This may be attributed to the increase in the void fraction that causes the local HTC to decrease. Yin *et al.* [11] conducted experiments to investigate the effects of inlet subcooling on the heat transfer and pressure drop characteristics of DI water flowing through open microchannels while boiling. According to the findings, boosting inlet subcooling delayed the emergence of a stratified flow, a flow regime that was vulnerable to local wall dry-out, and as a result raised a local two-phase HTC measured adjacent to a channel exit. In a single copper microchannel, Mohammed and Fayyadh [12] experimented to study the effect of inlet subcooling on the coefficient of heat transfer using water as the working fluid. The results have shown that increase in the HTC was associated with the increase in the degree of subcooling.

2.1.1.2 Mass flux

Numerous studies on flow boiling in conventional microchannels have found that the effect of mass flux vanished at low heat fluxes, but that the mass flux increases at high heat fluxes or in the presence of convective boiling flow regimes in the channels resulting in a significant improvement in HTC. Harirchian and Garimella [13] performed tests using FC-77 at various mass fluxes and discovered that following the start of nucleate boiling, HTCs were independent of mass flux. Larger HTCs were discovered in situations with larger mass fluxes, which correlate to the heat fluxes that suppress bubble nucleation at the channel walls. Huang *et al.* [10] investigated the flow boiling characteristic for R1233zd(E) in the silicon microchannel heat sink at the subcooled condition with ranges of mass fluxes. They reported that at the subcooled region and at the region with very low vapor quality, the local HTC decreased slightly with the increase in the mass flux, whereas increased for the same heat flux, at the region with relatively high vapor quality, and the local HTC increased significantly with the increase in the mass flux. In the studies by Markal *et al.* [14], Mohammed and Fayyadh [12], and Al-Nakeeb *et al.* [9], it was reported that when distilled water is used as the working fluid in microchannel heat sinks, HTCs in two-phase increased dramatically with an increase in the mass flux. Al-Zaidi *et al.* [15] used straight microchannel heat sinks and discovered a tenuous relationship between mass flow and HTC. The flow boiling heat transfer of HFE-7100 in a multi-microchannel heat sink in a subcooled environment was the subject of their research, with wall heat fluxes and mass fluxes varying from 25.1 to 191.6 kW/m^2 and 50 to 250 kg/m^2 s, respectively. In contrast, the impact of mass flux was generally insignificant in a two-phase value, as was observed in the studies by Harirchian and Garimella [13], and Bertsch *et al.* [16]. When mass fluxes in the low heat flux zone decreased, somewhat higher HTCs were found. This was explained by the impact of mass flux on the vapor quality exit of the channels. Likewise, Fayyadh *et al.* [17] conducted experiments in a multi-microchannel for a range of mass flux and heat flux using R134a as working.

Another scenario of the effect of mass flux is that an increase in mass flux will cause deterioration for heat transfer rate in the microchannel. Costa-Patry *et al.* [18] found that HTCs decreased with the increase in mass flux between 594 and 1,051 kg/m^2 s at low vapor quality because the bubbles coalesced earlier and the dry-out was more intermittent.

Alam *et al.* [19] observed that for a given heat flux, average HTCs in their silicon nanowire microchannel array increased to a maximum with the increase in mass flux up to 400 kg/m^2 s but significantly decreased with the further increase in the mass flux.

2.1.1.3 Heat flux

Conflicting heat transfer patterns have been found in the literature with regard to the increase in heat flow and how it affects the HTC. The HTC increased when the heat flow increased, according to several research. The large amount of nucleate boiling as well as the expansion in the number of active nucleation sites in the channels at higher heat fluxes are attributed to the enhancement of HTCs in relation to heat flux. This improvement was seen when higher heat fluxes were applied. When the trend of the HTC became unresponsive to further increases in the level of heat flow outside the region where convective boiling was intended to be prevalent in the channels, the influence of heat flux may also become insignificant at their higher levels. There are several problems connected to the corresponding heat transfer systems that have not yet been resolved.

Qu and Mudawar [20] investigated the boiling of DI water in microchannels using several probes. Researchers found that the HTC increased with the increase in the mass flux but decreased with the increase in the vapor quality. This was contrary to what they expected to see. On the HTC, it was discovered that the heat flow had a very minor influence. Steinke and Kandlikar [21] investigated the boiling of water in a system consisting of several microchannels. They said that the heat transmission coefficient dropped with the increase in the vapor quality, and nucleate boiling was demonstrated to be the predominant heat transfer process. Huh and Kim [22] examined the boiling of water in a microchannel in the shape of a rectangle. They discovered that the coefficients of heat transmission were almost unaffected by the amount of mass flux or the quality of the vapor. Despite the fact that they interpreted these trends simply as nucleate boiling being the dominating flow pattern, they also observed annular flow as being the predominant flow pattern. The same trend was also noted by Madhour *et al.* [23]. Their study focused on the two-phase flow boiling of refrigerant R134a inside a copper multi-microchannel heat sink for microelectronic central processing unit cooling applications. They found that the HTC increased with heat flux and was independent of mass flow rate. The same trend was also noted under certain operating conditions by Tang *et al.* [24]. In this study, flow boiling experiments on the microchannel were carried out utilizing DI water as a working fluid to investigate the impact of the mass flux and inlet subcooling at a range of heat flux on its two-phase convective heat transfer enhancement and pressure drop characteristics. These findings led the authors to the conclusion that the primary heat transmission mechanism during the initial phases of boiling was nucleate boiling.

It was reported that the predominant mode of heat transport was by forced convective boiling. Jones and Garimella [25] investigated the influence of surface roughness in microchannels on heat transfer at a range of heat flux using DI water as the working fluid. Researchers discovered that when heat flow rose, the boiling HTC also did so. However, beyond the area where convective boiling was thought to predominate in the channel, the HTC trend became unresponsive to additional increases in heat flux level. Similar results were reported by Costa-Patry *et al.* [26], when investigating the heat transfer characteristics of flow boiling of R236fa and R245fa in multi-microchannel at saturated conditions. Authors observed that the HTCs for R236fa and R245fa increased with wall heat flux up to 130 kW/m^2, when became less dependent on wall heat fluxes.

Within the scope of the experiments performed by Mohammed and Fayyadh [27], a heat sink consisting of a single square channel with a hydraulic diameter of 0.300 mm was used to determine the HTC for the flow boiling of the fluid. According to the findings, it is clear that the range of the heat flow has the greatest impact on the HTC, and the dominant mechanism was convective boiling.

However, according to Sumith *et al.* [28], nucleate and convective boiling may both take place simultaneously. Lee and Garimella [29] discovered the two-heat transfer mechanism while studying saturated flow boiling of DI water in an array of multi-microchannels built of silicon. At heat fluxes ranging from low to medium, the local HTC grew virtually linearly with heat flux. In contrast, the saturated HTC became largely insensitive to heat flux as the heat flux progressed.

The effect of fluid properties on flow boiling heat transfer was markedly distinct compared to DI water as reported by Agostini *et al.* [30]. Three patterns in heat transmission are discovered in this research's microchannel flow boiling investigation employing the working fluids R236fa and R245fa. HTCs for R245fa reduced as heat flux increased when there was a large mass flux but low heat flux. On the other hand, in the region of low heat flow, the behavior of R236fa in terms of heat transfer remained unaffected. At medium heat flux levels, the HTCs for both fluids rose with the heat flux. A subsequent increase in heat flux in the high heat flow area instead resulted in a decrease in HTC. In an experimental study performed by Markal *et al.* [14], under saturated conditions, the flow boiling heat transfer of DI water in straight parallel silicon microchannels was investigated. It was found that nucleate boiling and convective boiling are the two primary processes responsible for the transport of heat. These are distinguished from one another by the formation of bubbles and the evaporation of thin layers of liquid, respectively. In addition, according to their flow visualization, it was found that higher heat fluxes caused a reverse flow, that prevented nucleated boiling in a channel.

Criscuolo *et al.* [31] used a multi-microchannel evaporator to explore the flow boiling of R1234yf, R1234ze(E), and R134a under a variety of heat flux conditions, from the boiling incipience to the critical heat flux. Researchers observed that three distinct boiling regimes could be distinguished based on how heat and mass fluxes affected the local two-phase HTC as follows: the two-phase local HTC in boiling regime I increased with the heat flux and was independent of the mass flux. When the flow was in boiling regime II, it behaved differently where the mass flux had a noticeable impact (*i.e.,* the flow was independent of heat flux). Ultimately, at boiling regime III, the two-phase local HTC declined dramatically with the heat flux.

In the research experiments carried out by Dalkılıç *et al.* [32], a multi-microchannel with a hydraulic diameter of 0.421 mm was used to find the HTC at high mass and heat flux for the flow boiling of the refrigerant R134a. It is seen that the rise in heat flux causes the increase in a HTC at low vapor quality, while the effect of mass flux is ineffective. With the increase in the heat flux, convective boiling became the dominant of heat transfer mechanism, and the HTC increased with the increase in the vapor quality and mass flux until a dry-out point. A similar mechanism was observed by Al-Nakeeb *et al.* [9], who experimented with a single microchannel using DI water at a range of mass flux and heat flux (based on the wall).

2.1.2 Two-phase pressure drop

2.1.2.1 Inlet subcooling

Some investigators discussed the effect of the degree of subcooling on the flow boiling pressure drop in microchannels. Lee and Mudawar [33] studied the effect of inlet subcooling for HFE-7100 in four horizontal rectangular multi-microchannels with different aspect ratios (width to height) in the range of 0.25–0.41 on flow boiling pressure drop. They conducted their study at very low inlet coolant temperatures, *i.e.,* 0 and −30°C, and high mass fluxes, ranging from 670 to 6,730 kg/m^2 s. They reported that increasing the subcooling of incoming liquid decreases two-phase pressure drop because of the decrease in void fraction caused by strong condensation at bubble interfaces and decreased likelihood of bubble coalescence. Deng *et al.* [34] carried out experiments in a multi-microchannel using ethanol as the working fluid. They found that two-phase pressure drop across the microchannels decreased notably with the increase in the inlet subcooling. This is due to that at higher subcooling conditions, the two-phase region in the heat sink is small. Huang and Thome [6] studied the effect of the inlet subcooling of R245fa and R236fa in multi-microchannel at the subcooling degrees of 5.5, 10, and 15 K. They found that increasing subcooling degree from 5.5 to 10 K significantly reduced the total pressure drop in a heat sink, but increasing subcooling degree further to 15 K had no effect. Tang *et al.* [24] conducted experiments in the multi-microchannel at three different inlets subcooled temperatures using water in works with the inlet pressure of around 1 bar. According to the them, when the input subcooling temperature was raised from 10 to 70 K, the flow boiling pressure decreased from 5.5 to 1.5 kPa. This was explained by the channels' decrease in the void percent with the increase in subcooling.

To control heat discharge from high-power density electronic devices with high hotspot heat-generating, diamond multi-microchannels were used by Yang *et al.* [35]. Researchers investigated the influence of the inlet condition on the two-phase pressure drop flow boiling using ammonia as the working fluid. The pressure drop that occurs under the saturated inlet condition is greater than that which occurs under the subcooled inlet condition for a given heat flux and mass flux. Additionally, the effect of the inlet condition is more obvious when higher mass fluxes are present. This may be explained by the presence of an upstream single-phase flow when the input state is subcooled, and the length of the single-phase zone becomes longer as the mass flux is increased. Because of this, the intake subcooling has less of an impact on the pressure drop, particularly at greater mass fluxes.

Also well as, Ramesh *et al.* [36] conducted experimental investigations of subcooled boiling channel pressure drop of water in an aged copper microchannel. The experiments were carried out for three inlet temperatures with a range of mass flux and heat flux. The authors observed that for a specified heat flux, when the degree of subcooled fluid temperature is decreased, the pressure drop is increased due to an increase in void fraction. The effects of degree of subcooling of inlet on the flow boiling pressure drop in a single rectangular brass microchannel was investigated by Al-Nakeeb *et al.* [9] for operating system pressure of 1 bar using DI water as the working fluid. The experiments were performed at a range of mass flux from 300 to 600 kg/m^2 sec and heat flux (based on the wall) from 5.4 to 376.5 kW/m^2 for two degrees of subcooling, 20 and 35 K. The results show that increase in the degree of subcooling led to a decrease in the channel pressure drop, due to condensation of the strong bubble in the channel, as well as the flow had a small void fraction.

Contrarily, Yin *et al.* [11] showed that subcooling had a significant impact on the two-phase pressure drop only at low heat fluxes when the channels were dominated by bubbly and slug flow. The authors hypothesized that this was due to the promotion of nucleate boiling that was brought about by a reduction in inlet subcooling, which raised the frictional pressure drop in the channels. The subcooling impact in this location was minimal due to the shorter subcooled length and predominance of stratified flow under conditions of increased heat flux. Likewise, Mohammed and Fayyadh [27] conducted experiments to investigate the subcooled flow boiling pressure drop at the copper microchannel using DI water as a working fluid. The experiments were performed in a microchannel with an aspect ratio of 1 for various experimental conditions, mass fluxes of 1,700 and 2,100 kg/m^2, and heat fluxes in the range of 78–800 kW/m^2 at two degrees of subcooling of 21 and 31 K. The obtained results show that the two-phase pressure drop increased as the degree of subcooling increased. Also, Zhao *et al.* [37] observed an increase in the pressure dropped with the increase in the inlet subcooling when the conducted experiments were carried out in microchannel heat sink with a large aspect ratio of 3.33. This occurrence is due to the greater liquid viscosity and the rapid spike in pressure drop brought by stratified slug flow. The flow boiling experiments were carried out at a range of mass fluxes for four inlet temperatures.

2.1.2.2 Mass flux

The two-phase pressure drop increases as mass flux increases. This is because larger mass flux results in higher wall shear stress and energy loss from fluid acceleration, which in turn increases the system's frictional pressure drop and acceleration pressure loss components. The impact of mass flux on pressure drop in flow boiling at microchannels is reported; a higher heat sink pressure drop has been associated with the increase in the in mass flux.

Harirchian and Garimella [13] observed that when mass flux increased in silicon microchannel heat sinks, both the single-phase and two-phase pressure drop of FC-77 steadily increased. In this research, the authors changed the number and size of the channels while maintaining a base area of 12.7 mm × 12.7 mm. Line slope of pressure drop in the two-phase region increases as the channel width decreases, resulting in much larger pressure drops for smaller channels at higher heat fluxes. The highest pressure loss was approximately 6 kPa in the heat sink arrangement with 24 channels with 400 µm wide, while it increased to almost 24 kPa when the width of the microchannel was decreased to 100 µm. Even though a large channel width may lead to low values of pressure drop with conditions of high mass flux and heat flux, the results of prior studies in the low pressure drop relatively could potentially be attributed to the fluid's properties as given by Agostini *et al.* Part III [38]. The authors investigated the pressure drop during flow boiling in multi-microchannels using R236fa and R245fa as working fluids. Researchers examined the pressure drop across a multi-microchannel heat sink and observed that the refrigerant fluid of R236fa had a maximum pressure drop than refrigerant R245fa. However, they noted that these comparisons were not identical because of the various manifold configurations between the heat sinks. Therefore, the authors used a homogeneous model to show that the two-phase pressure drop for R235fa is lower, that is resulting from the lower vapor density of the fluid. A similar study was done by Holcomb *et al.* [39] with using DI water as the working fluid in multi-microchannel. The trend variation of pressure drop with channel size and mass flux (*i.e.* an increase in pressure drop with increases in either channel size or mass flux) is as expected and consistent with the results of Harirchian and Garimella. Also, Costa-Patry *et al.* [26] showed findings that were comparable for both fluids (R245fa and R236fa) within the range of mass flux and base heat fluxes.

However, because the parts of friction and acceleration pressure loss are related to the square of the mass velocity, the pressure drop gradient about vapor quality is typically steeper at higher mass fluxes. Dário *et al.* [40] investigated the effect of mass flux and inlet subcooling of R134a on the pressure drop across parallel microchannels during flow boiling.

Balasubramanian *et al.* [41], Hu *et al.* [42], and Li *et al.* [43] observed that at specific heat flux, the pressure drop increased with the increase in mass flux.

Remarkably, Chen and Garimella [44] studying the flow boiling of FC-77 at a constant input subcooling of 26 K revealed that the silicon microchannel heat sink's mass flux was insensitive to changes in pressure drop. The authors speculated that this may be because frictional pressure loss and acceleration pressure loss had opposing effects. On the other hand, overall pressure loss rose at higher mass fluxes after initially decreasing as a function of mass flow.

2.1.2.3 Heat flux

In general, flow boiling pressure drop in microchannel heat sinks employing a variety of working fluids, including DI water, rises with the increase in the heat flux or vapor quality. Many studies have been done on this topic, including those by Qu and Mudawar [45], Markal *et al.* [14], Mohammed and Fayyadh [27], and Al-Nakeeb *et al.* [9], Agostini *et al.* Part II 2008 [30], FC-77 Harirchian and Garimella [13], HFE-7100 Al-Zaidi *et al.* [15], Huang *et al.* [10]. It's usually because of the rise in flow resistance caused by creating bubbles in the channels, along with the rise in heat flux and vapor quality in the saturated boiling zone. This leads to a rise in the two-phase pressure drop with vapor quality. This is because the two-phase pressure drop in the microchannel heat sinks is linked to the flow patterns that happen in the channels. In straight microchannel heat sinks, slug, extended bubble, or annular flow were seen to be the main flow patterns. As heat flux and vapor quality went up, pressure drop often went up too. A similar observation was found by Kim *et al.* [46] carried out tests utilizing FC-72 in a conventional rectangular fin heat sink and found that though pressure drop throughout the channel increases in terms of vapor quality, it was mostly independent of the heat flux. A number of investigators came to a conclusion that the frictional pressure drop in the heat sink was far greater than the acceleration pressure loss component.

2.1.3 Effect of parameters on flow instability

The flow boiling instability, the boundary of the stable area, and the instability features are significantly influenced by the heat transfer system's operational parameters (amplitude and frequency). The following will be presented to examine the flow instability-influencing variables of inlet subcooling, mass flux, and heat flux.

A number of investigators investigated the influence of sub cooling degree on flow instability in microchannel. So, at large inlet subcooling conditions, flow reversal and parallel channel interaction were cited by Prajapati and Bhandari in 2017 [47] as the main causes of flow instabilities in microchannels. However, previous studies reported contradicting results about the dependence of the flow instability on the degree of subcooling. Mitigation two-phase oscillations, including the inlet temperature and pressure, were found by Chen *et al.* [48] for higher inlet subcooling. This was explained by the delayed transition to annular flow, a phase in which flow reversal was typically seen in heat sink. Also, Lee *et al.* [49] reported that increased intake subcooling was shown to reduce pressure drop oscillations in microchannels when using R134a. Low liquid intake temperatures, the scientists reasoned, had a greater dampening effect on vapor backflow into the inlet plenum. Intermittent dry-out, which primarily affected annular flow and significantly reduced HTCs in this area, was increased by pressure drop oscillations. Lee and Karayiannis [7] observed that due to the delay in slug flow formation, increased input subcooling diminished the amount of flow oscillations.

Contradictorily, high inlet liquid subcooling created significant flow oscillations, as found by previous researchers. A similar observation was found by Chen and Wu [50]. They carried out experiments to investigate the impact of inlet subcooling on the stability of flow boiling in a microchannel using DI water as the working fluid. The experiments were conducted with inlet subcooling degrees of 70, 40, and 20 K, mass fluxes and base heat fluxes of 446–963 kg/m^2 s and 17.5–407.2 W/cm^2, respectively.

The influence of intake subcooling on flow instabilities is also contingent on the fluid characteristics of the fluid being used. Deng *et al.* [51] observed contrasting effects of subcooling with ethanol and water in the same pin-fin re-entrant microchannel heat sink. With water, greater intake subcooling levels exacerbated flow instabilities, but with ethanol, higher inlet subcooling levels decreased two-phase flow oscillations in a test segment. The oscillations of ethanol often had a greater amplitude than those seen while using water, according to the scientists. The effectiveness of intake subcooling on flow instabilities is determined by heat flux and mass flux in addition to fluid characteristics. Al-Nakeeb [52] carried out experiments in a single microchannel at a range of inlet subcooling, mass flux, and wall heat flux using DI water and binary mixture (ethanol and water) in the concentration range of 5–20%. It was found that at a moderate wall heat flux, the oscillations for binary mixture with 5% concentration as compared to the DI water decreased as the inlet subcooling increased. In contrast, the instability of the flow boiling occurs when a wall heat flux is higher at same mass flux. The author also found that the flow oscillation decreased with the increased mass flux at the same heat flux. A similar observation was found by Liu *et al.* [53] when they experimented with a single rod channel having system pressure of 0.1–1.0 MPa with different mass fluxes. In summary, there are contradictory accounts of influence for an inlet subcooling on flow instabilities in the microchannel.

3 Flow boiling characteristic through coated microchannel/ microtubes

In order to create surface topologies with nucleation sites, surface modification techniques like surface coatings and sandpaper treatment were used. These techniques may aid in reducing boiling incipient superheat, enhancing heat transfer and enhancing the critical heat flux limit in two-phase microchannel systems, and extending the critical heat flux boundary of boiling systems. In addition to suppressing two-phase flow instabilities in multi-microchannel heat sinks, this method was developed, as reviewed in Prajapati and Bhandari [47].

3.1 Wettability

Surface wettability has a significant impact on boiling heat transfer. A surface is said to be wettable (*i.e.,* hydrophilic) if the contact angle between a liquid and a solid substrate is less than 90° and hydrophobic if the contact angle is greater than 90°. In settings with a decreased heat flow, the reduced amount of free energy necessary for nucleation causes the early commencement of boiling in hydrophobic surfaces. However, when exposed to larger heat fluxes, the abrupt development of bubbles across the surface leads to a reduced rate of heat transfer for hydrophobic surfaces when compared to hydrophilic surfaces.

During testing on the flow boiling, many researchers used microchannels/microtubes having surfaces that are either hydrophilic or hydrophobic or both to examine how wettability of the surface affects the bubbles formation and heat transfer. Hence, Choi *et al.* [54] studied the impact of wettability on the flow boiling of water in a channel with a hydraulic diameter of 0.5 mm. Water was found to have a 25° contact angle with photosensitive glass that was left uncoated, making it hydrophobic; yet, water was measured to have a 105° contact angle with glass that had been coated with octadecyltrichrolosilane (OTS), making it hydrophilic. It was found that at a given mass flux condition, the hydrophilic surface caused local dry-out at lower vapor quality than a hydrophobic surface. After drying out, HTCs significantly decreased. In the hydrophobic channel, annular flow predominated, while elongated bubbly flow predominated in the hydrophilic channel. Moreover, flow visualization revealed that the annular liquid film was unstable and that bubble nucleation was seen in a film, which increased heat production. As a result, the hydrophobic channel gets a higher HTC. Similarly, Phan *et al.* [55] examined how the surface wettability of the microchannel affected the flow boiling characteristic of water using five samples of the microchannel. That had been coated by different degrees of wettability; silicon oxide (SiOx), titanium (Ti), diamond-like carbon (DLC), and carbon-doped silicon oxide (SiOC) surfaces with static contact angles of 26°, 49°, 63°, and 104°, respectively. While a SiOx coating had the lowest local HTCs compared to the other coatings, although local HTCs did not seem to change appreciably as vapor quality increased in the channel. In addition, the SiOx surface seemed to have the maximum level of wettability in the experiment. For SiOC hydrophobic surface, nucleate boiling occurs even at subcooling conditions. However, as previously indicated, the high bubble formation activity led to speedy bubble coalescence, which in turn accelerated wall dry-out and deteriorated the channel's HTCs.

On the other hand, some engineering applications require heat transfer to be higher. Hence, the heat transfer characteristics are highly dependent on surface morphology which have nucleation sites and pore density that leads to efficient heat transfer (*i.e.,* hydrophobic surface). So, Sujith Kumar *et al.* [56] studied the impact of decreasing wettability of copper substrates coated with diamond and carbon nanotubes (CNTs) on the flow boiling heat transfer and contrasted them with bare sand-blasted copper substrates. The experiments were carried out with the same inlet subcooling and a variety of mass fluxes and heat flux using water as the working fluid. It was found that coatings reduce the wettability of the sandblasted surface and increase the hydrophobicity of coated surfaces. In other words, with an untreated surface, water had a contact angle of 54.9°, while contact angles of 135.5° and 89.9°, respectively, were achieved by carbon nanotube and diamond coatings. In addition, the results show that the hydrophobic channel coatings with a carbon nanotube improve the transfer of heat during boiling by increasing the density of bubbles that can form.

On the other hand, increasing coating thickness is caused by increasing surface wettability. Hence, Çikim *et al.* [57] studied the impact of coated thickness on improving heat transmission utilizing cross-linked polyhydroxy ethyl methacrylate (pHEMA) coats on microtubes of about 0.25–0.91 mm internal diameters using DI water as the working fluid. The findings showed that as the coating thickness rose from 50 to 150 nm, so did an effect that improved heat transfer by up to 126%. Because the crosslinked pHEMA coats are porous, they have more nucleation sites and more bubbles. This makes the boiling heat transfer better rise in the flow of heat and the quality of air.

Other researchers combined both properties, hydrophilic and hydrophobic surfaces, for coating surfaces and accessed its effects on the flow boiling characteristic. Nedaei *et al.* [58] investigated the effect of gradient wettability along the longitudinal microtube on the enhancement of flow boiling heat transfer using water as working fluid in it where they utilized two coatings, hydrophobic for polyperfluorodecylacrylate (pPFDA) and hydrophilic for pHEMA, in two stainless steel microtubes having a diameter of 0.5 mm. One of them was coated with pHEMA at the inlet and with pPFDA at the outlet, or a hydrophilic inlet and a hydrophobic outlet. The other microtube was set up differently, with a hydrophobic inlet and a hydrophilic outlet. It was found that both arrangements improved the HTCs relative to a bare stainless-steel tube, with a hydrophobic inlet/hydrophilic outlet having more significant effect on the enhancement. The explanation was attributed to the presence of more active nucleation sites near the inlet and greater wettability nearby the outflow. In the same group, Nedaei *et al.* [59] extended their study to evaluate the effects of varying wettability and increasing coating thicknesses on increased flow boiling heat transfer. In stainless steel microtubes with inner diameters of 0.6 mm and 0.9 mm, respectively, they raised the thickness of the coating layer made of pPFDA by 50 and 160 nm, respectively. A contact angle of the water on a bare surface (Si wafer) was 61°, whereas the contact angle of water on the surface with a 50 nm coating layer was 121°. This indicates that the surface with the coating layer has lower wettability and higher hydrophobicity. According to the findings, raising the thickness of the coating from 50 to 160 nm generated a modest reduction in the contact angle of water for both microtubes, which brought it down to 106°. This caused better heat transfer performance for microtubes having a thicker coating. The increased hydrophobicity and porous structure of pPFDA-coated microtubes result in more active nucleation sites, which is the cause of the higher HTC enhancement. Because of their reduced wettability, thicker coatings have higher HTCs, which made rewetting near the exit easier.

3.2 Mass flux and heat flux

As already mentioned, the formation of the flow pattern in microchannels is crucial for the improvement of heat transmission. In light of this, heat flux and mass flow circumstances may also affect how well heat transfer augmentation utilizing porous coatings works. Numerous investigations have discovered varied enhancement behaviors at various operating mass fluxes as well as a noticeable decline in heat transfer enhancement at high heat flux.

Khanikar *et al.* [60] looked at the thermal advantages of coating the bottom wall of a rectangular micro-channel with CNTs. DI water was used as the working fluid in experiments that were carried out in subcooled conditions with both a bare copper wall and a copper wall covered with CNTs at various mass fluxes and two different inlet temperatures. A carbon nanotube-coated channel showed a significantly higher critical heat flux limit of 270 kW/m^2 than a bare surface, that was 219 kW/m^2, the researchers have found, at the lowest mass flux condition. As the mass flux in both channels increased, the critical heat flux limit also increased. However, at high mass flux, the CNT coating was negative for instability. Therefore, research has been looked into using porous metal coatings as a potential CHF enhancement candidate and weakened instability. The CHF is influenced by coating porosity, coating thickness, and particle size and shape. Bai *et al.* [61], employing the solid sintering method, investigated the effect that porous metallic coatings on microchannels had on the flow boiling heat transmission. The working fluid was an alcohol that had lost all of its water. When compared to the microchannel that was left uncoated, the porous metal-coated microchannel was shown to have a much greater capacity for the transmission of heat. Because of an increase in nucleation density, a greater heat transfer rate was achieved despite a decrease in vapor quality. Moreover, the results revealed significant flow instability minimization. Similarly, nanowires (NWs) are a group of materials that have the properties of wettability, porosity, and wicking structure. Li *et al.* [62] investigated the effect of the wettable bottom surface of the silicon microchannel on flow boiling characteristics by coating it with integrated silicon nanowires (SiNWs). The experiments were performed at a range of mass fluxes and heat flux using DI water as the working fluid. According to the results, with a mass flux of 119 kg/m^2 s, the coated channels' HTCs were lower at the boiling incipience than those of the plain channel. However, HTC in a nanowire-coating channel was mostly greater than that in the plain channels for mass fluxes between 238 and 571 kg/m^2 s. Also, the results showed that the instability of the temperature was suppressed. In other words, in a nanocoated microchannel, a stable flow boiling trend was observed over a wide range of heat flux.

According to the previous CNTs in Khanikar *et al.* [2], there may be problems if the nanocoating was not created using the correct fabrication techniques, leading to detachment of nanocoating and deterioration in heat transfer. The coating of heated surfaces with nanoparticles by nanofluid pool boiling is one straightforward method for obtaining nanocoating. By pool-boiling ethanol-based alumina (Al_2O_3) nanofluid, Morshed *et al.* [63] formed an Al_2O_3 nanocoating in a single Cu microchannel with a hydraulic diameter of 672 m. The experiments were performed at a range of heat and mass flux at subcooled conditions using DI water as the working fluid. Results of flow boiling experiments showed that the nanocoated microchannels could only increase the CHF by 35–55% and that the HTC was slightly lower for the nanoparticles-coated surface than for the bare surface. Similar effects have been observed when the wettability of the surface is increased. So, Kaya *et al.* [64] examined the effect of coating microtubes with pHEMA on the flow boiling enhancement. Flow boiling heat transfer experiments were conducted on microtubes at two mass flux values using DI water as the working fluid. Experimental results obtained from the coated microtubes were compared to their bare surface counterparts, and found that the coated surfaces demonstrated an increase of up to 24 and 109% in CHF and HTC, respectively.

As covered above, the effect of CNTs and diamond coating over copper substrates on flow boiling heat transfer performance was investigated by Sujith Kumar *et al.* [56]. The experiments were performed at the subcooled condition for a range of mass flux and heat flux using demineralized water as the working fluid. The results showed that, in comparison to bare Cu or Cu substrate covered with diamond, the critical heat flow was significantly higher on surfaces coated with CNTs. For a mass flux of 283 kg/m^2 s, an improvement of 21.6% in the CHF was noted. The authors Sujith Kumar *et al.* [65] extended their work. They looked at the impact on CHF and boiling HTC of spray pyrolyzed Fe-Al_2O_3-TiO_2 composite coating with varying amounts of iron (0, 1.8, 3.6, and 7.2%). The coatings were around 20 μm thick. Water contacted the sandblasted copper plate at a contact angle of 75.5°, which fell to 40.1° at a concentration of 7.2% Fe. Consequently, porosity increased from 45 to 72%, which corresponds to Fe concentrations of 0 and 7.2%. According to the results, when comparing the enhanced surface to sandblasted copper surfaces at a fixed mass flux, all demonstrated a significant improvement in boiling HTC and CHF. The largest percentage improvement of 52.39 and 44.11% in the CHF and HTC, respectively, of water were obtained for 7.2% Fe-doped surface at a mass flux of 88 kg/m^2 s. This enhancement results from the coated surface with high porosity and hydrophilicity. In their subsequent tests, published by Sujith Kumar *et al.* [66], it was revealed that the spray pyrolyzed ZnO-Al_2O_3 coatings also caused improvements in both the flow boiling HTC and the critical heat flux for water compared to pure ZnO coatings. Maximum improvements of 44.6 and 29.7% in CHF and HTC, respectively, occur at a mass flux of 88 kg/m^2 s. Enhanced hydrophilicity and the presence of micro-cavities are responsible for this improvement.

Flow boiling of dielectric fluids in microchannels is among the most promising embedded cooling solutions for high-power electronics. However, it is normally limited by their poor thermal conductivity and small latent heat. To compensate for this problem, suggest NWs could potentially improve the flow boiling heat transfer of dielectric fluids in microchannels. Yang *et al.* [67] investigated the flow boiling performance of low-surface-tension dielectric coolant (HFE-7000) in the microchannels with NWs. They carried out experiments in subcooled conditions at a range of mass flux and heat flux. As compared to the bare microchannel, due to the improvement of nucleate boiling and evaporation, it was shown that utilizing SiNWs boosted the HTC at heat fluxes less than 120 W/cm^2 by a substantial amount, up to 344%. Capillarity-enhanced phase separation caused the pumping power to be lowered by up to 40%. In addition, CHF was enhanced by up to 14.9%.

As mentioned above, pHEMA (hydrophilic) and pPFDA (hydrophobic) coatings were used by Nedaei *et al.* in 2016 [58] to alter the wettability of 0.5 mm stainless steel microtubes along the longitudinal direction. Out of the two coating arrangements, the hydrophobic inlet/hydrophilic outlet configuration provided enhancement heat transfer with the increase in the heat flux until 8,000 kW/m^2 at the mass flux of 9,500 kg/m^2 s, but rapidly declines as the heat flux increases further. The differences in the heat transfer enhancement behavior at various heat flux, however, remained unexplained. In the same group, Nedaei *et al.* [59] extended their work as covered above. They studied the development of the flow boiling heat transfer in stainless steel microtubes by coating them with pPFDA. The experiments were carried out at subcooled conditions for two microtubes with different diameters, 0.6 and 0.9 mm at a range of mass flux and heat flux using DI water. According to the results, pPFDA-coated microtubes considerably improved heat transfer performance compared to the bare surface microtube. Improvement in the heat transfer at two-phase is related to increasing the heat flux, and the largest enhancement was pertinent to the microtubes with an inner diameter of 0.9 mm at the mass flux of 8,000 kg/m^2 s. The mass flux increase had a positive effect on the HTC two-phase.

However, the effect of coated microchannels with SiNWs on the flow boiling characteristic was investigated by Alam *et al.* [68]. They carried out experimental studies on a flow boiling for HFE 7100 through microchannel with plain walls and SiNWs at a range of heat and mass flux. When compared to a bare wall, it was observed that the SiNW surface considerably reduced flow boiling instabilities in terms of wall temperature fluctuation and pressure drop. Moreover, SiNW performs HTC at a dramatically higher level than plain wall microchannels (up to 400% improvement). On the other side, CHF is slightly affected by nanostructured surfaces. Likewise, Wang *et al.* [69] investigated the effect of etched SiNWs on a bottom and the side wall for the parallel silicon channel on flow boiling characteristics using DI water as the working fluid. The experiments were carried out at a range of mass flux and heat flux. Under identical heat flux and mass flux conditions, the silicon nanowire-coated channels exhibited a reduction of around 15 K in wall superheat degree, dropping from 75 to 60 K. Also, at a mass flux of 250 kg/m^2 s, the flow boiling heat transfer enhancement of water remained mostly unaltered while marginally increasing at higher heat fluxes. This is a result of the NWs' ability to prevent wall drying out by capillary-assisted rewetting. For a base heat flux around 1,000 kW/m^2, the peak improvement value of about 134% is observed at higher mass flux for 500 kg/m^2 s.

An impact of coating thermal conductivity on overall performance is crucial to keep in mind when contemplating the use of coatings to improve performance. High thermal conductivity coatings can lead to increased efficiency, where Gupta and Misra [70] fabricated more thermally conductive Cu-TiO_2 nanocomposite coatings on mini channel copper heating surfaces. The experiments were performed at subcooled conditions within a range of mass flux and heat flux using DI water as the working fluid. Results showed that the maximum enhancement was by CHF 143%, and HTC 153% was attained on a developed coated surface at lower mass flux. In the same group, Gupta and Misra [71] extended their work with the same test rig and operation conditions but with different nano-compositing Cu-Al_2O_3 coating surfaces. It was found that the maximum augmentation in CHF and HTC by 176 and 200%, respectively, are achieved at the mass flux of 53 kg/m^2 s.

Recently Lee *et al.* [72] investigated the effect of porous coatings microchannel on heat transfer enhancement of flow boiling. The experiments were performed at subcooled conditions within the range of mass flux and heat flux using HFE-7200 as a working fluid. As compared to the plain microchannel, results showed that enhancement in microchannel flow boiling heat transfer was influenced by mass flux and may reach up to 44% at low heat fluxes, where the nucleate boiling mechanism is dominant.

results in a reduced pressure drop during flow boiling in microchannels [32].

4 Summary and scope

In the present research, a thorough examination of the parametric influences, encompassing the effects of mass and heat flux, and inlet subcooling, on microchannel flow boiling characteristics has been published. This review covered a wide range of topics: It could be said that contradictory trends about the impact of operating parameters on flow boiling behavior in microchannels were reported in the literature, and they were as follows.

4.1 Flow boiling heat transfer

There are disagreements about the heat transfer mechanism (s) and the impact of heat and mass flux on boiling heat transfer in microchannels. According to Table 1, some research works have indicated that the predominant heat transfer mechanism is nucleate boiling. Others, however, stated that both nucleate and convective boiling mechanisms might occur simultaneously or that convective boiling is the predominant heat transfer mechanism. The purpose of this study was an attempt to clarify the heat transfer mechanism in microchannel with DI water as working fluid. In addition, various groups of researchers disagree on the impact of inlet subcooling on heat transfer rates. While one team of investigators discovered that rising the subcooling degree reduced flow instabilities, another team of investigators observed that a higher subcooling degree enhanced flow oscillations. Similar to this, A few investigations found that inlet subcooling has little impact on the HTC for flow boiling, although some found that flow instabilities were suppressed, resulting in increased heat transfer rates. Increasing the inlet subcooling usually makes the critical heat flux occur later.

4.2 Flow boiling pressure drop

At elevated levels of heat flux, it has been observed that the pressure drop in two-phase flow increases due to a higher proportion of empty space in the channels. However, some studies have found smaller pressure drops at higher heat fluxes and acceleration losses. Additionally, increasing subcooling can dampen two-phase flow oscillations, which

4.3 Enhancement of flow boiling characteristics

When it comes to boiling enhancement (HTC, CHF, reduced instability flow), which is affected by fluid properties, porosity, wettability, and surface roughness, the role of structures must be taken into consideration in promoting bubble nucleation, preventing drying, and the durability of these surfaces. As the review elucidated, porosity, wettability, and surface roughness can be achieved by coating surfaces. From previous work, one can observe that CNTs and NWs are more efficient and appreciably increase the boiling characteristics, but the durability of these surfaces with repeated trial runs will impact the lifetime and performance of the appliances where deformation of these surfaces was observed at higher flow rate conditions during the flow boiling experiments [12].

Porous coatings containing micro- and nano-cavities have drawn a lot of attention due to their capacity to provide a high density of nucleation sites, a large surface area, and wettability that improves the gas/vapor entrapment. To manufacture microporous coatings on the heating surface, numerous methods have been used, as indicated in Table 2. However, in boiling heat transfer applications, erosion (oxidation) occurs on metal-coated surfaces. Considering this problem, the researchers found that the oxide-coated layer will be more appropriate with respect to the durability of the surface in high thermo-fluid conditions. However, it is well known that metal oxides are generally hydrophilic due to the presence of metal cations, oxygen anions, and hydroxyl groups on the surface. In a recent study, nanocomposite or oxide layers developed on the base substrate, mainly for boiling systems, when considering the effect of coating thermal conductivity on overall performance. Coatings with high thermal conductivity can improve performance. Examples of high thermal conductivity microporous coatings used to improve the efficiency of flow boiling heat transfer include Cu-TiO_2 (Gupta and Misra [70]) and Cu-Al_2O_3 (Gupta and Misra [71]).

Graphene nanoplatelets (GNPs), the wonder material, attracted worldwide attention in the field of science and technology due to excellent thermal properties (*i.e.*, k = 900–5,000 W/m K), which makes it fascinating in heat transfer. The remarkable thermo-physical characteristics of graphene nanoplatelets prompt the authors to think about using them as a coating material on the microchannel's heating surface.

Table 1: Published literature for flow boiling heat transfer in microchannel

Author	Substrates/D_h, μm/ number of channel/Geometry	Mechanism	Operation condition *G* (kg/m^2 s)/*q* (kW/m^2)	Fluid/Tin (K)/Tsat (K)/Pin (bar)/
Liu and Garimella [3]	Copper/384 and 588/ single/	NB	221–1,283/1,290	DI water/340–368/–/–
Agostini *et al.* [4]	Silicon/336/multi (67)/	NB	281–1,501/36–1,900	R245fa, R236fa/(0–19)/ (296.7–316.9)/1.41–2.73
Ong and Thome [5]	Stainless steel/1,030/ single/	NB	1,000–2,000/2.3–250	R134a, R236fa and R245fa/(2–9)/ 304/–
Huang and Thome [6]	Silicon/100/multi (67)/	NB	1,250–2,750/200–640	R245fa and R236fa)/298 and/313/–
Lee and Karayiannis [7]	Copper/475.5/multi (44)/	NB	200/25.9–180.7	HFE-7200/343, 338 and 328/348.1/1
Korniliou and Karayiannis [8]	Copper/1,000/single/	NB and CB	200 and 400–600/105–455	DI water/368, 358, and 323/ 373/1.05
Al-Nakeeb *et al.* [9], Al-Nakeeb [47]	Brass/420/single/	NB and CB	300–600/2.08–371.7	DI water/353 and 338/373/1.01 (ethanol/water)/338/363.8, 359.8, and 356.3/1.013
Houxue *et al.* [10]	Silicon/10,000/multi (67)/	NB and CB	500–2,750/60–500	R1233zd(E)/302.2/308/ 0.0864–0.2168
Yin *et al.* [11]	Oxygen-free copper/300,266.67/ multi (6,12)/	NB and CB	174–374/2,149–13,551	DI water/323, 338 and 353/373/–
Mohammed and Fayyadh [12]	Copper/300/single/	CB	1,700 and 210/78–800	DI water/332, 342 and 352/373/1
Qu and Mudawar [20]	Copper/349/multi (21)/	CB	135–402/200–13	DI water/303–333/373/1.17
Steinke and Kandlikar [21]	Copper/207/multi (6)/	NB	157–178/5–930	DI water/295/373/1
Huh and Kim [22]	Polydimethylsiloxane/100/ 1/	NB	90, 169 and 267/200–500	DI water/373/Patm.
Madhour *et al.* [23]	Copper/174.36/multi (100)	NB	205–100/25.7–180	R134a/333/336/1.7
Tang *et al.* [24]	PIMN/172.55/multi (16)	NB and CB	200, 301 and 500/0–80	DI water/363, 333 and 303/373/
Jones and Garimella [25]	Copper/500/single	NB	200, 600 and 1,000/ 0–3,000	DI water/360/–/–
Costa-Patry *et al.* [26]	Silicon/147.6/multi (135)	NB and CB	499–1,100/130–1,400	R236fa and R245fa/303.5/303.5/ 1.81–3.26
Sumith *et al.* [28]	Stainless steel/1, 450/single	NB and CB	23.4–152.7/10–715	DI water/371/373/–
Lee and Garimella [29]	Silicon/160, 290, 400, 540/multi (10–60)	NB and CB	46–126 (ml/min)/ 100–3,400	DI water/363–368.1/373/–
Markal *et al.* [14]	Silicon/100/multi (29)	CB	151, 195, 238, 281, and 324/71–131	DI water/323/373/1.
Criscuolo *et al.* [31]	Copper/475.5/multi (17)	NB and CB	415–1,153/0–310	R1234yf, R1234ze(E), and R134a/ –/303.5–313.5/–
Dalkılıç *et al.* [32]	Copper/421.45/multi (27)	NB and CB	800 and 1,000–1,200/ 50–460	R134a/–/291, 296 and 301/–
Harirchian and Garimella [39]	Silicon/160–749/multi (2–60)/	NB and CB	250–1,600/0–400	FCC-350/368/–/–
Al-Zaidi *et al.* [15]	Copper/460/multi (25)/	NB	50–250/21.7–335.3	HFE-7,100/327.6/332.6/1

(Continued)

Table 1: *Continued*

Author	Substrates/D_h, μm/ number of channel/Geometry	Mechanism	Operation condition *G* (kg/m² s)/*q* (kW/m²)	Fluid/Tin (K)/Tsat (K)/Pin (bar)/
Bertsch *et al.* [16]	Copper/1.090–0.54/multi (17, 33)/ ▭	NB	20–350/0–22	R134a, R245fa/–/353–303/–
Fayyadh *et al.* [17]	Copper/420/multi (25)/ ▭	NB	50–300/11.46–403.1	R134a/–/–/279.5/22
Alam *et al.* [19]	Silicon nanowire/234/multi (5) ▭	NB	100–600./0–3,500	DI Water//373/–
Lee and Mudawar [33]	Copper/175.5, 200, 334.1, 415.9/ multi (4) ▭	NB and CB	670–6,730 /0–6,000	HFE 7100/273–243/
Deng *et al.* [34]	Copper/786/multi (14) Ω	NB and CB	125, 200 and 300/0–650	DI Water/311–341/373–
Qi *et al.* [35]	Diamond/280/multi (37) △	NB and CB	98–1,200/4,739–10,004.	Ammonia/293/298, 303 and 308/–
Ramesh *et al.* [36]	Copper/658/1/ ▭	NB	528 and 825, 1,188/ 260–110	DI water/303, 323, and 343/ 373/1.013
Zhao *et al.* [37]	Copper/598/multi (46) ▭	NB and CB	153 and 229/ 180.81–2,165.15	DI water/278–358/373/–
Holcomb *et al.* [39]	Silicon/299,531,640/multi (3) ▭	NB and CB	250750 and 1,150/0–1,800	DI water/368/373/–
Dário *et al.* [40]	Copper/770/multi (9) ○	NB and CB	250–1,000/5– 220	R134a/–/–/0.6–0.9
Balasubramanian *et al.* [41]	Copper/300/multi (40) ▭	NB and CB	100–133/1,400	DI water/363/373.-
Li *et al.* [43]	Silicon/766/multi (40) ▭	NB and CB	83–442/0–10	Acetone liquid/302/329/1
Chen and Garimella [44]	Copper/839/multi (10) ▭	NB and CB	30–50 ml/min/09–16	FC-77/–/–
Kim *et al.* [46]	Copper/1,000/multi (18) ▭	NB and CB	24.2–230.0/71.12–213.4	FC-72//59.8–71.5°C/–
Lee *et al.* [49]	Copper/1,000/multi (100)/ ▭	NB and CB	75.92–208.79/3.99–28.209	R134a/–/–/6.88–7.31
Bogojevic *et al.* [42]	Silicon/194/multi (40) ▭	NB	72.2–433.3/78, 267, 356 and 445	DI water/298–344/373/–
Deng *et al.* [51]	Copper/750, 776/multi (14) ▭	NB and CB	200–300/0–1,067	DI water and ethanol/ 333–363/–373/
Kingston *et al.* [44]	Glass/500/single ○	NB and CB	200–800/–	HFE-7100/303–333/338/1.675
Chen and Wu [50]	Silicon/114/multi (14) ▭	NB and CB	446–963/175–4,072	DI water/303333 and 353/373/–
Deng *et al.* [51]	Diamond/500/multi (15) Ω	NB and CB	125, 200 and 300/0–1,100	DI water/333, 363/373/–
Liu *et al.* [53]	Glass/19,000/single ▭	NB and CB	800–2,000/–	DI water/343–363/373/0.1–1.0

5 Results

As per the comprehensive review, the study found that various parameters significantly impact flow boiling heat transfer in microchannels and coated microtubes. The critical parameters that affect flow boiling heat transfer include instability, heat flux, mass flux, and degree of subcooling.

The study also found that the presence of coatings on the microtubes can enhance the heat transfer performance by improving the surface wettability and promoting bubble nucleation. Furthermore, the use of microchannels and coated microtubes in flow boiling heat transfer can result in higher HTC and reduced pressure drop compared to conventional heat exchangers.

Table 2: Published literature for coating flow boiling heat transfer

Author	Substrate/working fluid/ D_h, µm/ number of channel/geometry	Coating material	Wettability	Particle size/coating thickness/ concentration	Coating method	Operation condition G (kg/ m^2 s)/q (kW/m^2)/Tin(K) Tsat(K)/Pin (bar)/	Enhancement comparison with plain surface (HTC/ CHF/instability)
Choi *et al.* [54]	Glass/DI water/500/ single	OTS	105°	–/–/	Dipping	25, 75/10–430/373/368/–	Increase/–/increase
Phan *et al.* [55]	Pyrex wafer/DI water/960/ single	SiOx, Ti, DLC, SiOC	26°, 49°, 63° and 104°	—	PVD and CVD	100/30–80/293/373/1	Increase/–/–
Sujith Kumar *et al.* [56]	Copper/DI water/22, 222/ single	Diamond, CNTs	90° and 133°	—	CVD	283, 348, 427/50–500/373/ 363/1	Increase/increase/
Cikim *et al.* [57]	–/DI water/249, 507, and 908/single	(pHEMA)	37°—45°	–/50, 100 and 150 nm/–	CVD	5,000, 20,000/ 25,000–35,000/–/373/ q.22–15.52	Increase/increase/–
Nedaei *et al.* [58]	Stainless steel/DI water/ 502/single	(pHEMA), (pPFDA)	109°, 43°	–/150 nm/–	CVD	9,500/5,000–1,100/–/373/–	Increase/–/–
Nedaei *et al.* [59]	Stainless steel/DI water/ 889, 600/single	(pPFDA)	121° and 106°	/50 and 160 nm/–	CVD	6,000, 7,000 and 8,000/ 3,000–1,300//373/	Increase/–/–
Khanikar *et al.* [60]	Copper/DI water/715/ single	CNTs	—	–/60 nm./–	MPCVD	86, 228 and 368/218–404/ 305–333/1.13	–/Increase/–
Bai *et al.* [61]	Copper/anhydrous ethanol/554/multi (50)	Metallic porous coatings	—	30, 55, 90 µm,	Sintering	200 and 500/ 200–1,200/–/–/–	–/–/decrease
Li *et al.* [62]	Silicon microchannel/DI water/222.22/multi (14)	Silicon nanowires	—	—	Nanowire-coated	119–571/0–1,100/–/373/–	Increase/increase/decrease
Morshed *et al.* [63]	Copper/DI water/672/ single	$Cu\text{-}Al_2O_3$	97.5° and 67°	10 µm	Copper-electrodeposition	33, 70, and 142/0–600/295/ 373/–	Increase/increase/–
Kaya *et al.* [64]	Metal microtubes/DI water/249, 507, and 998 µm/single	pHEMA	75°,45°	30 nm	CVD	10,000 and 13,000/ 500–2,500/–/373/–	Increase/increase/–
Sujith Kumar *et al.* [65]	Copper/DI water/24,000/ single	$Fe\text{–}Al_2O_3\text{–}TiO_2$ composite	75.5°–40.1°	2 µm	Spray pyrolysis	88 and 248/50–1,100/343/ 373/–	Increase/increase/decrease
Sujith Kumar *et al.* [66]	Copper/DI water/24,000/ single	$ZnO\text{-}Al_2O_3$	136°, 81.4°, 41.2° and 32.9°	24–9 nm/26–2.9 µm/–	Spray pyrolysis	88 and 248/150–600/343/ 373/–	Increase/increase/–
Yang *et al.* [67]	Copper/dielectric fluid (HFE 7000)/234/multi (5)	Si NWs	—	–/300 nm/–	Advanced nanofabrication techniques	1,018–1,527/0–1,600/ 313–353/–/1	Increase/increase/–

(Continued)

Table 2: *Continued*

Author	Substrate/working fluid/ D_h, μm/ number of channel/geometry	Coating material	Wettability	Particle size/coating thickness/ concentration	Coating method	Operation condition *G* (kg/m^2 s)/*q* (kW/m^2)/Tin(K) Tsat(K)/Pin (bar)/	Enhancement comparison with plain surface (HTC/ CHF/instability)
Alam *et al.* [68]	Silicon/HFE 7100/234/multi (5)	SiNW	—	20 nm/–/–	Electroless electrochemical etching	400–1,600/200–1,200/–/–/–	Increase/increase/decrease
Wang *et al.* [69]	Pyrex glass/DI water/ 311.76/single	Silicon dioxide, Teflon	43.32°, 123.97°	100 nm	Sputtering	103–203/25.6 and 786.1/297/ 373/1	Increase/–/decrease
Gupta and Misra [70]	Copper/DI water/2,608/ single	Copper–Titanium oxide	38°	42 μm	Copper electrodeposition	361, 268, 113, and 53/ 50–1,600/–/373/–	Increase/increase/–
Gupta and Misra [71]	Copper/DI water/2,608/ single	Copper–alumina	65°, 48° and 32°	45 and 53 μm	Copper electrodeposition	53, 113, 268, and 361/ 100–2,000/–/373/–	Increase/increase/–
Lee *et al.* [72]	Copper/HFE-7200/475/ multi (44)/	Copper nickel alloy	12°	5–10 μm	Porous nanocoating	200–400/24.5–160.7/339/ 349/–	Increase/increase/–
Present work	Brass/DI water/420/ single	Al_2O_3, Al_2O_3–Graphene	71.44° and 68.38°	25 μm	Nickel electroplating deposition	250–450/1.8–702/345, 353 and 361/373/1.013	

Experimental and numerical studies have been conducted to investigate the impact of these parameters, and it has been observed that the heat transfer performance is highly dependent on the operational conditions and the geometrical features of the microchannels and coated microtubes.

The effect of instability was found to have a significant impact on flow boiling heat transfer in microchannels and coated microtubes. The presence of flow instability can lead to enhanced heat transfer performance, but it can also result in undesirable effects such as flow reversal and flow maldistribution.

The study also found that the heat flux and mass flux have a direct impact on the heat transfer performance in microchannels and coated microtubes. Higher heat flux and mass flux can result in higher HTCs, but they can also lead to excessive pressure drop and flow instability.

Moreover, the degree of subcooling was found to have a significant impact on flow boiling heat transfer in microchannels and coated microtubes. Higher degrees of subcooling can lead to enhanced heat transfer performance, but they can also result in undesirable effects such as flow instability and flow maldistribution.

Overall, the review provides valuable insights into the critical parameters that affect flow boiling heat transfer in microchannels and coated microtubes and highlights the need for further research in this area to optimize the design and performance of microscale heat transfer systems.

6 Discussion

6.1 Main findings of the present study

The present study conducted a comprehensive review to investigate the impact of various parameters on flow boiling heat transfer in microchannels and coated microtubes. The main findings of this study indicate that instability, heat flux, mass flux, and degree of subcooling are critical parameters affecting heat transfer performance. Coatings on microtubes were found to enhance heat transfer by improving surface wettability and facilitate bubble nucleation. Microchannels and coated microtubes demonstrated higher HTCs and reduced pressure drop compared to conventional heat exchangers. These findings have significant implications for the design of microscale heat transfer systems in areas such as electronics cooling, chemical processing, and energy conversion.

6.2 Comparison with other studies

When comparing the findings of the present study with previous research, it was observed that similar trends were identified regarding the positive effects of higher heat flux and mass flux on HTCs. However, this study also highlighted the complex nature of the impact of instability on heat transfer performance, including both positive and negative effects. The findings align with and contribute to the existing body of knowledge. However, it is important to note that variations in experimental setups, fluid properties, and surface characteristics among different studies may influence the observed effects.

6.3 Implication and explanation of findings

The findings of this study have significant implications for the design and optimization of microscale heat transfer systems. The use of coatings on microtubes can improve heat transfer performance through enhanced surface wettability and bubble nucleation. The study highlights the need to carefully consider operational conditions and geometrical features to achieve optimal heat transfer performance while avoiding adverse effects such as flow instability and excessive pressure drop. The complex nature of instability and its impact on heat transfer performance necessitate further research to better understand the underlying mechanisms.

6.4 Strengths and limitations

One of the strengths of this study is the comprehensive review, which provides a holistic understanding of the impact of parameters on flow boiling heat transfer in microchannels and coated microtubes. The study considers multiple critical parameters and their interplay, contributing to a more comprehensive analysis. However, it is important to acknowledge the limitations of this review. The findings are based on existing literature, which may have inherent biases and limitations. The generalizability of the results may be influenced by variations in experimental setups, fluid properties, and other factors. Future experimental studies with standardized setups and methodologies are recommended to improve the reliability and robustness of the findings.

6.5 Conclusion, recommendation, and future directions

In conclusion, the comprehensive review sheds light on the significant impact of parameters on flow boiling heat transfer in microchannels and coated microtubes. Coatings on microtubes can enhance heat transfer performance, and microchannels exhibit favorable characteristics compared to conventional heat exchangers. The study recommends further research to optimize the design and performance of microscale heat transfer systems, considering factors such as instability, heat flux, mass flux, and degree of subcooling. Future studies should focus on gaining deeper insights into the underlying mechanisms and employing advanced experimental and numerical techniques to improve the understanding and optimization of microscale heat transfer systems.

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