The Open European Journal of Applied Sciences (OEJAS)
المجلة الأوروبية المفتوحة للعلوم التطبيقية
|| Volume || 2 || Issue || 1 || 2026 ||
ISSN (e): 3062-3391, Pages 18-31
https://easdjournals.com/index.php/oejas/index
Open access

Enhancement of Heat Transfer in Microchannel Heat Sinks Using Nanofluids

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تعزيز انتقال الحرارة في المبددات الحرارية ذات القنوات الدقيقة باستخدام الموائع النانوية

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Date of Submission: 08-12-2025 **Date of acceptance: 16-02-2025** **Date of publishing: 03-03-2026**

Abstract

Microchannel heat sinks offer a compact way to remove high heat flux from small devices. Their small channels create a large heat transfer area. Nanofluids are often proposed as better coolants for these systems. They can raise thermal conductivity and improve heat removal. Yet they can also raise viscosity, pressure drop, and stability risk. This paper reviews public experimental and numerical studies on heat transfer enhancement in microchannel heat sinks using nanofluids. The review gives more weight to practical studies, because they show what can work in real devices. The literature shows that alumina-water, copper oxide-water, and titanium dioxide-water nanofluids can improve average heat transfer coefficient and reduce thermal resistance under many test conditions. The best gains usually appear at low or moderate particle loading, careful dispersion, and suitable Reynolds number. The gains become weaker when viscosity growth, particle clustering, erosion risk, or pumping power are ignored. Recent studies also show that channel design matters as much as coolant choice. Spoiler cavities, circular passages, and serpentine layouts can change mixing and boundary layer growth. The main finding of this review is simple. Nanofluids can improve microchannel cooling, but only when thermal benefit is judged together with hydraulic cost, long-term stability, and material compatibility. The paper closes with design guidance, research gaps, and a balanced view for future work.

Keywords: microchannel heat sink, nanofluid, convective heat transfer, thermal resistance, pressure drop, electronics cooling, alumina-water nanofluid.

الملخص

توفر المبددات الحرارية ذات القنوات الدقيقة وسيلة مدمجة لإزالة الفيض الحراري العالي من الأجهزة الصغيرة. إذ تؤدي القنوات الصغيرة إلى إنشاء مساحة كبيرة لانتقال الحرارة. وغالبًا ما تُقترح الموائع النانوية باعتبارها سوائل تبريد أفضل لهذه الأنظمة، لأنها تستطيع زيادة التوصيل الحراري وتحسين إزالة الحرارة. ومع ذلك، فإنها قد تؤدي أيضًا إلى زيادة اللزوجة، وارتفاع هبوط الضغط، وزيادة مخاطر عدم الاستقرار.

تستعرض هذه الورقة الدراسات التجريبية والعددية المنشورة حول تعزيز انتقال الحرارة في المبددات الحرارية ذات القنوات الدقيقة باستخدام الموائع النانوية. وقد أعطت المراجعة وزنًا أكبر للدراسات العملية، لأنها تُظهر ما يمكن تطبيقه فعليًا في الأجهزة الحقيقية.

تشير الأدبيات إلى أن الموائع النانوية المكونة من أكسيد الألومنيوم–الماء، وأكسيد النحاس–الماء، وثاني أكسيد التيتانيوم–الماء يمكن أن تحسن متوسط معامل انتقال الحرارة وتقلل المقاومة الحرارية تحت العديد من ظروف الاختبار. وعادةً ما تظهر أفضل النتائج عند استخدام تراكيز منخفضة أو متوسطة من الجسيمات، مع تحقيق تشتت جيد للجسيمات واختيار عدد رينولدز المناسب.

وتصبح هذه المكاسب أقل فعالية عندما يتم تجاهل زيادة اللزوجة، أو تكتل الجسيمات، أو مخاطر التآكل، أو القدرة المطلوبة للضخ.

كما أظهرت الدراسات الحديثة أن تصميم القنوات لا يقل أهمية عن اختيار سائل التبريد. إذ يمكن للتجاويف المسببة للاضطراب، والممرات الدائرية، والتصميمات المتعرجة أن تؤثر في عملية الخلط ونمو الطبقة الحدية.

وتتمثل النتيجة الرئيسية لهذه المراجعة في أن الموائع النانوية يمكن أن تحسن تبريد القنوات الدقيقة، ولكن فقط عندما يتم تقييم الفائدة الحرارية بالتزامن مع التكلفة الهيدروليكية، والاستقرار طويل الأمد، والتوافق مع المواد.

وتختتم الورقة بإرشادات تصميمية، وفجوات بحثية، ورؤية متوازنة للأعمال المستقبلية.

الكلمات المفتاحية: لمبدد الحراري ذو القنوات الدقيقة، المائع النانوي، انتقال الحرارة بالحمل، المقاومة الحرارية، هبوط الضغط، تبريد الإلكترونيات، مائع أكسيد الألومنيوم–الماء النانوي.

1. Introduction

Electronic devices keep shrinking, yet their heat load keeps rising. This creates a strong thermal bottleneck in power electronics, chips, and compact energy systems. Microchannel heat sinks became important after the early work of Tuckerman and Pease. Their study showed that liquid cooling in very small channels could remove high heat from a small area (Tuckerman & Pease, 1981).

A modern review reached the same broad conclusion. Microchannel heat sinks remain one of the best options for high power electronics because they offer large surface area, small size, coolant saving, and high heat transfer coefficient (Yu et al., 2024). Another recent review states that microchannel systems are now central to thermal design in microchips and MEMS devices (Ghani et al., 2024).

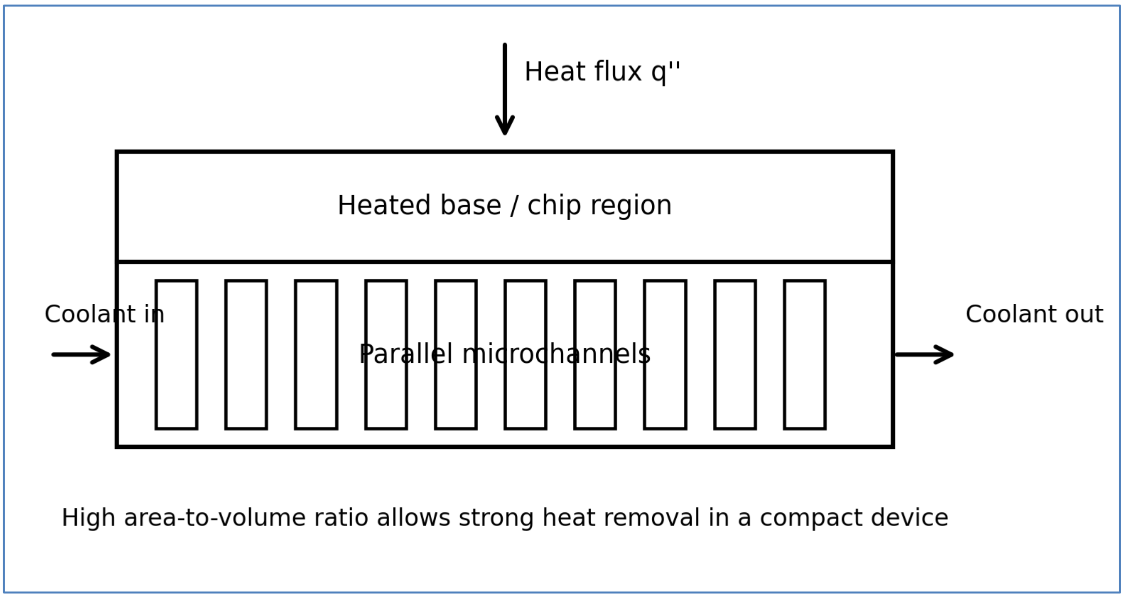


Figure 1 Working principle of a rectangular microchannel heat sink. Author-created figure based on Tuckerman and Pease (1981), Yu et al. (2024), and Ghani et al. (2024).

Water is often used in these channels because it is cheap and simple. Still, water has limits when heat flux rises further. Nanofluids were proposed to push performance higher. These fluids suspend very small solid particles in a base liquid. The goal is to raise heat transfer without changing the device footprint (Wang et al., 2022; Eneren et al., 2022).

The idea looks attractive, but the design problem is not one-sided. Better heat transfer may come with higher viscosity, larger pressure drop, pump burden, sedimentation, corrosion, or fouling. Reviews now stress that the field still has mixed results and unresolved mechanisms (Eneren et al., 2022; Wang et al., 2022).

This paper studies the topic through public evidence. It brings together review articles, classic papers, and experimental studies from 1981 to 2025. The aim is not to claim new lab data. The aim is to build a clear research paper from reliable public work. The paper asks three questions. When do nanofluids help? What penalty do they create? What design choices make the benefit more realistic?

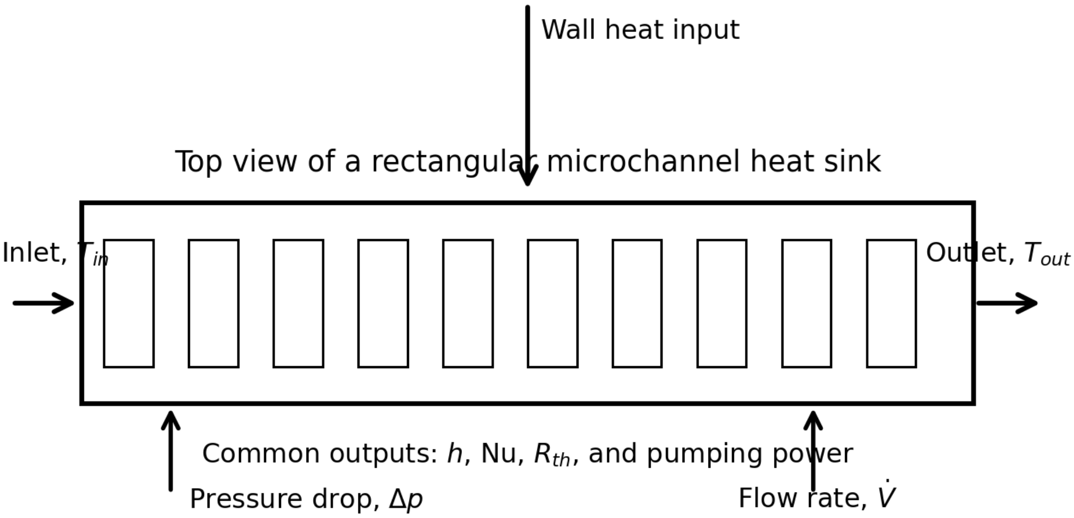


Figure 2 Main geometric and measured quantities in a rectangular microchannel heat sink. Author-created figure based on Yu et al. (2024) and Ghani et al. (2024).

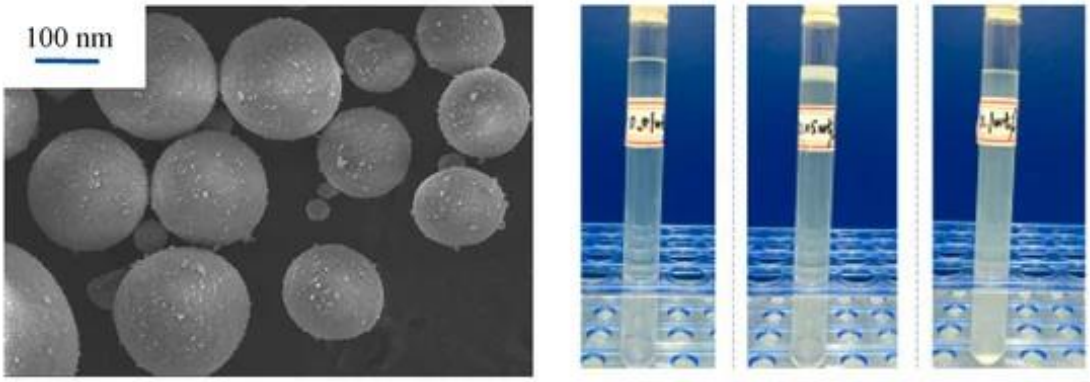
2. Fundamentals of Microchannel Cooling and Nanofluids

A microchannel heat sink is a solid plate with many narrow flow passages. Heat enters from the base. The coolant removes that heat while passing through the channels. Small hydraulic diameter raises surface area to volume ratio. This supports strong convection, especially near the channel entrance (Yu et al., 2024; Ghani et al., 2024). The main thermal outputs are heat transfer coefficient, Nusselt number, wall temperature, and thermal resistance. The main hydraulic outputs are pressure drop, friction factor, and pumping power. A good design lowers wall temperature and thermal resistance without a harsh rise in hydraulic cost. This balance is the central issue in nanofluid cooling (Wang et al., 2022; Eneren et al., 2022).

$$\boldsymbol{Nu = hD_h/k_f}$$
$$\boldsymbol{R_t h = (T_m ax - T_i n)/Q}$$
$$\boldsymbol{P_p ump = \Delta p \times \dot{V}}$$

Nanofluids use a base fluid, such as water, with particles smaller than about 100 nm. Common particles include Al2O3, CuO, TiO2, ZnO, silver, and carbon materials. A recent review explains that nanofluid performance depends on particle type, size, concentration, temperature, pH, shape, and preparation route (Wang et al., 2022). The main thermal promise comes from better thermal conductivity and stronger microscale mixing. Yet a second review warns that the actual mechanism is not fully settled. Particle clustering, stability loss, abrasion, erosion, and particle-wall interaction may alter both heat transfer and reliability (Eneren et al., 2022).

(a) SEM image of graphene nanosheets (b) SEM image of graphene/R141b nanofluid



(c) SEM image of Al_2O_3 nanoparticles (d) SEM image of Al_2O_3/R141b nanofluid

Figure 3 Graphene and Al2O3 nanofluids used in a public minichannel experiment. Reproduced from Zhou and Yin (2025), Nanomaterials, 15(14), 1054, under CC BY 4.0.

In practice, concentration must stay modest in many systems. Small loading can improve heat transfer. High loading often raises viscosity and pressure loss too much. Wang et al. (2022) note that added particles often raise viscosity and pressure drop in microchannels. That point is important, because a heat sink must work as a system, not just as a thermal surface.

3. Review Method and Source Selection

This manuscript uses public journal articles, open reviews, and public article records. Experimental studies were given priority. Numerical papers were used when they clarified flow structure, temperature field, or geometry effect. The selected sources span from the first microchannel cooling paper in 1981 to recent work in 2025 (Tuckerman & Pease, 1981; Li et al., 2025).

The source pool was narrowed by three filters. First, the study had to involve a microchannel or minichannel heat sink. Second, the coolant had to be a nanofluid or a close comparison case. Third, the study needed measurable outputs such as heat transfer coefficient, Nusselt number, wall temperature, friction factor, or pressure drop. This gave a practical evidence base rather than a broad materials survey (Eneren et al., 2022; Yu et al., 2024).

4. Public Experimental Evidence

The early experimental message was direct. Nanofluids could improve microchannel cooling, but they also raised hydraulic resistance. Chein and Chuang studied microchannel heat sink performance with nanofluids and reported slightly higher pressure drop than the base fluid. They also found that pressure drop increased with particle concentration (Chein & Chuang, 2007). This early paper framed the main trade-off that still shapes the field.

A strong later experiment was reported by Ho and Chen. They tested Al2O3-water nanofluid in a copper minichannel heat sink with ten parallel rectangular channels. Each channel was 50 mm long with a cross section of 1 mm by 1.5 mm. Compared with pure water, the nanofluid case gave significantly higher average heat transfer coefficient. The authors also judged the result against pumping power, which made the assessment more realistic (Ho & Chen, 2013).

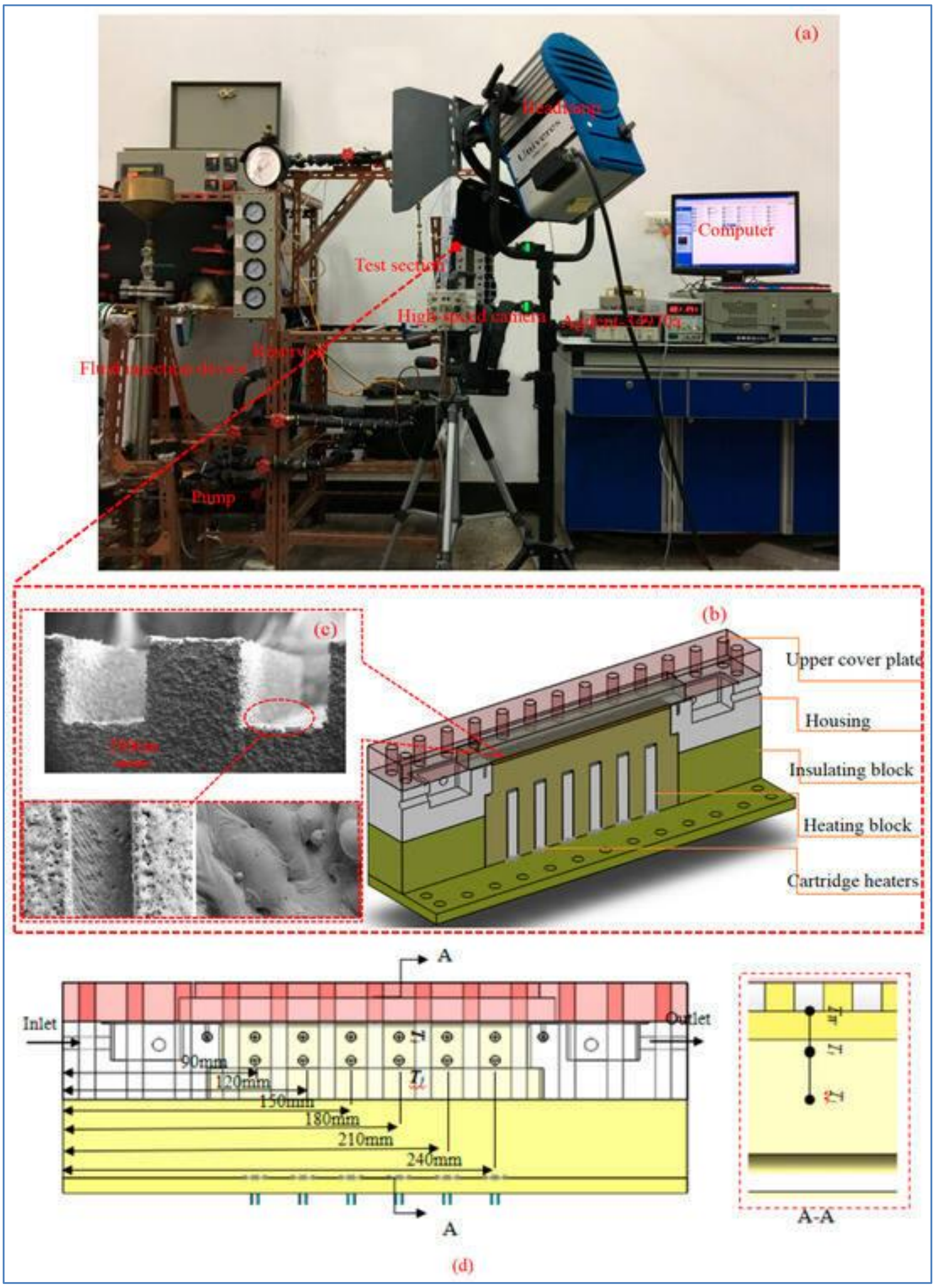
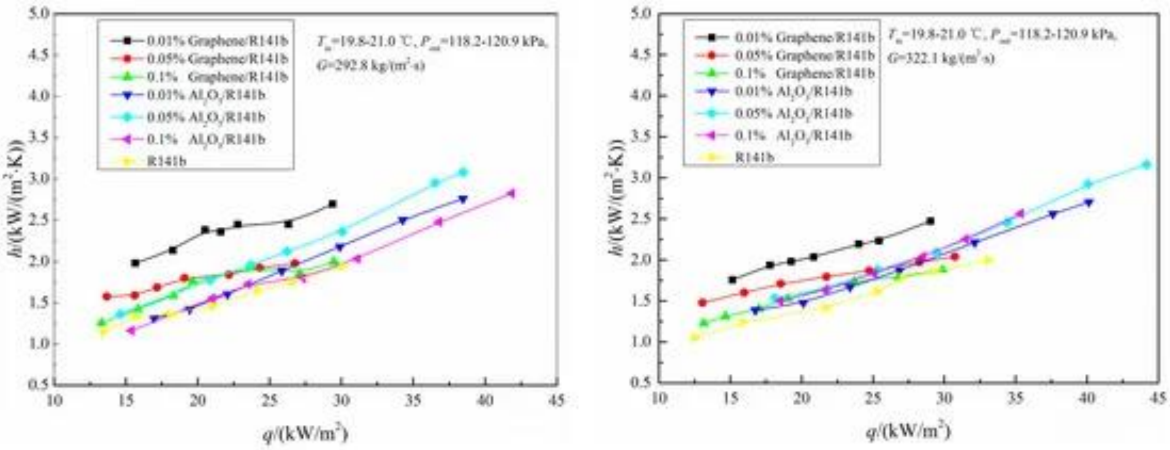


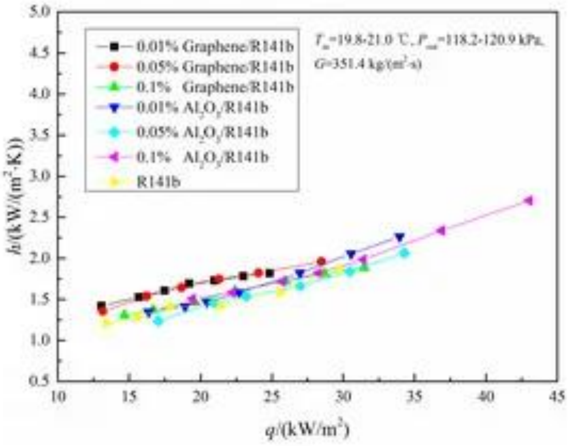
Figure 4 Experimental apparatus and test section for a 3D-printed minichannel heat sink. Reproduced from Zhou and Yin (2025), Nanomaterials, 15(14), 1054, under CC BY 4.0.

Later work compared different oxide particles in more complex channels. Sivakumar, Alagumurthi, and Senthilvelan tested Al2O3-water and CuO-water in a serpentine microchannel heat sink. They found that convective heat transfer rose with particle concentration. They also found that CuO-water gave higher heat transfer coefficient than Al2O3-water and the base fluid in their test range (Sivakumar et al., 2016).

A focused entrance-region study by Chabi and co-workers gave a useful benchmark. They tested CuO-water nanofluid with 0.1 and 0.2 vol% in a microchannel heat sink. The maximum increase in average heat transfer coefficient was about 40% for 0.2 vol% nanofluid at Reynolds number 1150. The gain weakened as Reynolds number rose further. This means the thermal gain can be strongest where boundary layers are still growing and particle effects remain noticeable (Chabi et al., 2017).



(a) G = 292.8 kg/(m²·s)   (b) G = 322.1 kg/(m²·s)



(c) G = 351.4 kg/(m²·s)

Figure 5 Variation of heat transfer coefficient with heat flux for graphene/R141b and Al2O3/R141b nanofluids. Reproduced from Zhou and Yin (2025), Nanomaterials, 15(14), 1054, under CC BY 4.0.

Moghanlou and co-workers compared Al2O3-water and TiO2-water nanofluids in a minichannel heat sink. Their test section used ten minichannels and was designed to cool thermoelectric generators. The particles were 20 nm in size. The study confirmed that oxide nanofluids can improve thermal behavior, but the hydraulic penalty remains part of the design picture (Moghanlou et al., 2020).

Jung and Park added another useful layer. They did not only report temperatures. They also measured velocity and temperature fields in a microchannel heat sink using Al2O3 nanofluid. Their results suggested that more energy moved from the channel cavity toward the upper flow region when nanofluid was used. This kind of field evidence is important because it links measured improvement to flow behavior, not only to bulk outlet temperature (Jung & Park, 2021).

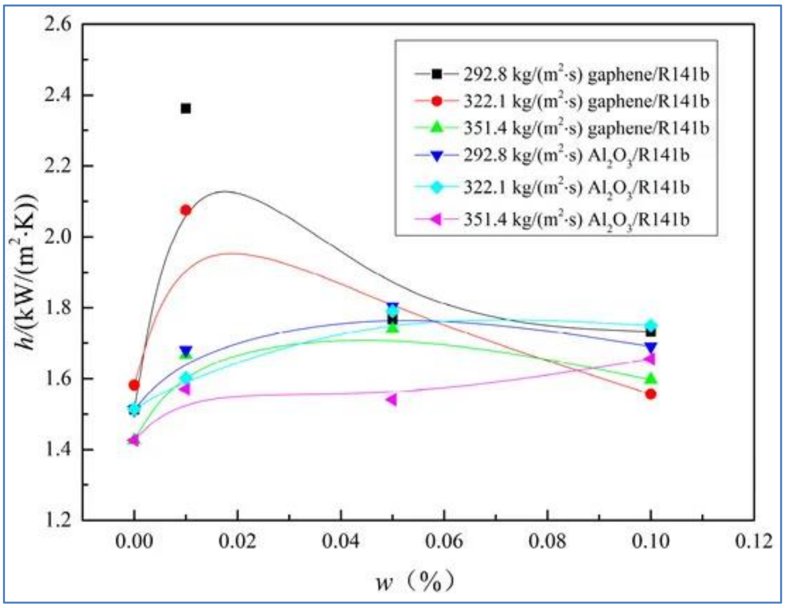


Figure 6 Effect of nanofluid concentration on heat transfer coefficient in the same public minichannel experiment. Reproduced from Zhou and Yin (2025), Nanomaterials, 15(14), 1054, under CC BY 4.0.

Some public studies used simple channel shapes. Others changed the geometry itself. Waqas and co-workers analyzed a six-circular-channel heat sink with nanofluid and reported the effects on heat transfer rate, Nusselt number, friction factor, thermal resistance, and chip reliability. Even though their work was numerical, it is useful here because it shows how channel shape can shift the full thermal-hydraulic balance, not only the heat transfer coefficient (Waqas et al., 2022).

Recent experimental work also moved closer to real power devices. Li and co-workers integrated a microchannel heat sink with spoiler cavities into high-power electronics and tested it with Al2O3-water nanofluid. Their 2025 study notes that integrated packages may reach heat flux near 100 W/cm2. They also report good agreement between experiment and simulation for the optimized cavity design. This shows that coolant enhancement and geometry enhancement should be studied together, not alone (Li et al., 2025).

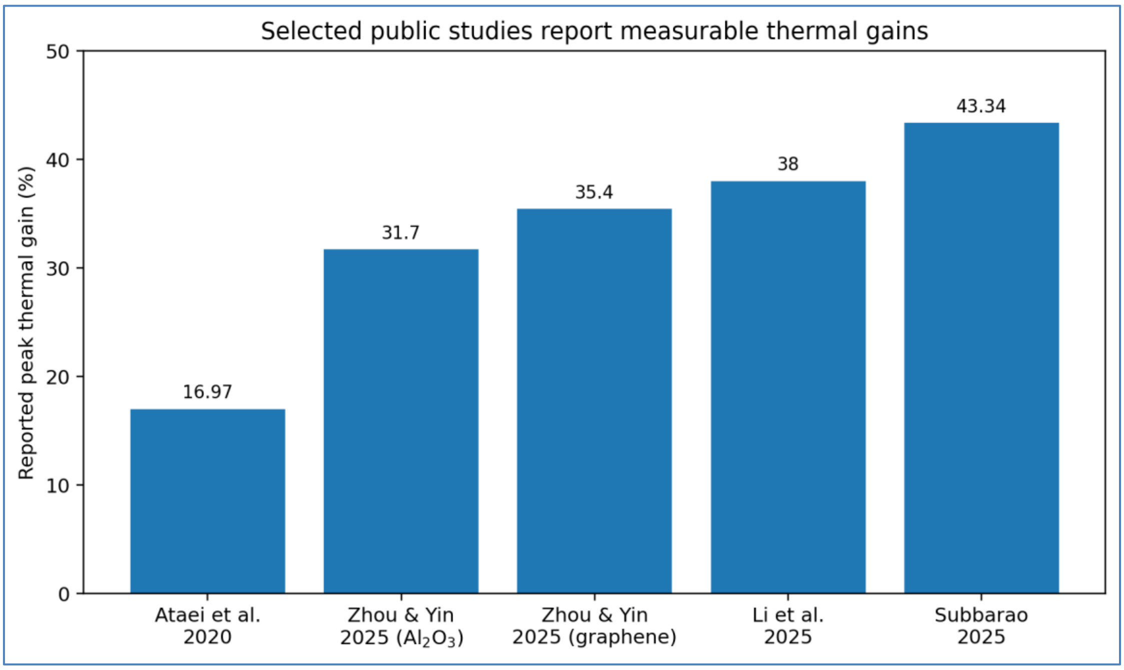


Figure 7 Reported peak thermal gains in selected public studies. Author-created figure from Ataei et al. (2020), Zhou and Yin (2025), Li et al. (2025), and Subbarao (2025).

A very recent experiment by Subbarao gives another practical lesson. Alumina nanofluids reduced back conduction by 51.54% compared with deionized water and lowered surface temperatures by 29%. The tested concentrations ranged from 1 to 4% by mass. This work is valuable because it looks at axial conduction, which becomes important in low Reynolds number microchannel systems (Subbarao, 2025).

The full evidence base does not say that nanofluids always win. Reviews still describe controversial results and incomplete agreement about enhancement mechanisms (Eneren et al., 2022). Yet the public experimental record does support one careful statement. When concentration, channel design, and flow rate are selected well, nanofluids can improve microchannel cooling in a measurable way. When these choices are poor, the hydraulic penalty can eat the benefit.

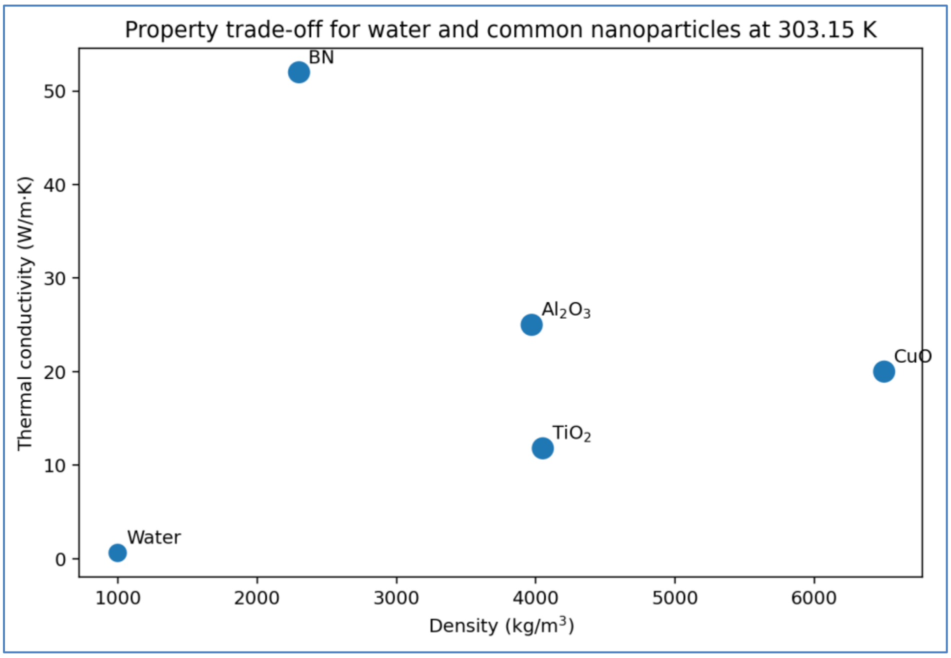


Figure 8 Density-conductivity trade-off for water and selected nanoparticles at 303.15 K. Author-created figure from Kaya (2022).

Table 1 Selected public studies on nanofluid cooling in microchannel or minichannel heat sinks

Study	Coolant	System or geometry	Main finding
Chein & Chuang (2007)	Nanofluid in MCHS	Experimental microchannel heat sink	Lower wall temperature was observed, but pressure drop was slightly higher and rose with concentration.
Ho & Chen (2013)	Al2O3-water	Copper sink, 10 rectangular minichannels, 50 mm length, 1 × 1.5 mm section	Average heat transfer coefficient was significantly higher than water when pumping power was also considered.
Sivakumar et al. (2016)	Al2O3-water and CuO-water	Serpentine microchannel heat sink	Heat transfer coefficient increased with particle concentration. CuO-water performed better than Al2O3-water in the tested range.
Chabi et al. (2017)	CuO-water, 0.1 and 0.2 vol%	Entrance-region microchannel test	Maximum average heat transfer coefficient gain was about 40% at 0.2 vol% and Re = 1150.
Moghanlou et al. (2020)	Al2O3-water and TiO2-water	Ten-minichannel heat sink for thermoelectric cooling	Oxide nanofluids improved thermal behavior, but the pressure penalty remained important.
Jung & Park (2021)	Al2O3 nanofluid	Microchannel heat sink with field measurements	More energy moved from the cavity to the upper region when nanofluid was used.

Subbarao (2025)	Alumina nanofluid, 1–4% m/m	Circular microchannels under low Re	Back conduction fell by 51.54%, and surface temperature fell by 29% compared with deionized water.
Li et al. (2025)	Al2O3-water	Spoiler-cavity microchannel heat sink integrated with IGBT device	Optimized cavity design showed good agreement between experiment and simulation under realistic device cooling.

A comparison across these studies shows that alumina-water is the most common test fluid. This is not accidental. Alumina gives a workable balance between preparation ease and measurable thermal gain. It may not always produce the largest enhancement, but it often produces the clearest repeatable dataset. That is why it appears in both classic and recent papers (Ho & Chen, 2013; Li et al., 2025).

Copper-oxide suspensions often report stronger local heat transfer gain. Yet they also tend to bring stronger hydraulic cost. The Chabi entrance-region study and the Sivakumar serpentine-channel study both support this point from different experiments. The lesson is not that CuO should be avoided. The lesson is that its use should be tied to a careful pump budget and channel design (Chabi et al., 2017; Sivakumar et al., 2016).

A second comparison issue is the way concentration is reported. Some studies use volume fraction. Others use mass fraction or weight percent. This simple reporting difference makes quick comparison harder than many readers expect. A study that looks conservative by mass may not be conservative by volume. Strong papers should therefore report both whenever possible and list the measured or estimated properties used in the analysis (Wang et al., 2022).

A third issue is the choice between local and average metrics. Local heat transfer coefficient can reveal where the gain forms. Average values are better for device-level judgment. Both are useful, but they answer different questions. Studies that report both are easier to trust because they connect mechanism with whole-system performance (Jung & Park, 2021; Chabi et al., 2017).

A fourth issue is the dominance of single-phase work. Single-phase experiments remain common because they are easier to control and interpret. Two-phase and boiling cases may remove more heat, but they also add flow instability, nucleation complexity, and more severe deposition concerns. For a paper centered on nanofluid microchannel heat sinks, the single-phase base remains the clearest path for reproducible comparison (Eneren et al., 2022; Yu et al., 2024).

5. Discussion

The reviewed studies show that nanofluid benefit does not come from one cause only. A part of the gain comes from improved thermal conductivity. Another part comes from altered near-wall transport, especially in the entrance region. Some channel shapes also increase mixing and renew the thermal boundary layer. This explains why coolant choice and geometry choice often interact strongly (Wang et al., 2022; Li et al., 2025).

The first design lesson is that concentration should stay controlled. Very small loading may give only weak gain. Very large loading can raise viscosity too much. Chein and Chuang saw pressure drop rise with concentration. Chabi and co-workers also showed that the best reported gain came at only 0.2 vol%, not at a very large fraction (Chein & Chuang, 2007; Chabi et al., 2017).

The second lesson is that average heat transfer coefficient alone can mislead. Ho and Chen judged performance against pumping power. That is the right habit. A heat sink that removes more heat but needs much more pump work may not be the best system choice. This is why many recent reviews call for thermo-hydraulic rather than thermal-only assessment (Ho & Chen, 2013; Wang et al., 2022).

The third lesson is that geometry can amplify or weaken nanofluid benefit. Straight channels are simple and easier to analyze. Yet serpentine paths, circular passages, and cavity-based designs can change the flow field enough to produce extra gain. Waqas et al. (2022) and Li et al. (2025) both support this view from different angles.

The fourth lesson is about stability and surface interaction. Eneren et al. review abrasion, erosion, and corrosion concerns in microchannel systems. These issues matter because channel passages are small. A tiny deposit can affect both flow and heat transfer. Good short-term results do not always predict long-term service behavior (Eneren et al., 2022).

The fifth lesson is that oxide particles remain the most practical family. Alumina appears often because it offers stable and repeatable performance with water. Copper oxide may give stronger thermal gain in some tests, but it can also bring a larger penalty. Titanium dioxide is often used when moderate enhancement and material simplicity are preferred (Sivakumar et al., 2016; Moghanlou et al., 2020).

Table 2 Main benefits and penalties of nanofluid use in microchannel heat sinks

Design factor	Likely benefit	Likely penalty	Evidence base
Low particle loading	Heat transfer can improve with modest hydraulic cost	Gain may be small if loading is too low	Chabi et al. (2017); Ho & Chen (2013)
Higher particle loading	Thermal conductivity may rise further	Pressure drop, clustering, and pump demand can rise	Chein & Chuang (2007); Wang et al. (2022)
Higher Reynolds number	Stronger convection and lower thermal resistance	Larger pressure loss and weaker relative particle effect	Chabi et al. (2017); Yu et al. (2024)
Complex channel geometry	More mixing and delayed boundary layer growth	Fabrication difficulty and uneven pressure field	Waqas et al. (2022); Li et al. (2025)
Long operation time	May prove practical value if stable	Sedimentation, abrasion, erosion, or fouling may appear	Eneren et al. (2022)

Table 3 Qualitative comparison of common nanofluids for microchannel cooling

Nanofluid	Strength	Weakness	Overall remark
Al2O3-water	Most tested and usually stable	Thermal gain is moderate, not extreme	Good baseline choice for experiments and practical prototypes.
CuO-water	Can give stronger heat transfer gain	Pressure drop and density effects may be larger	Useful when thermal gain is the main target and pumping penalty is acceptable.
TiO2-water	Chemically mild and widely available	Thermal gain is often lower than CuO or Al2O3	Reasonable for conservative designs with modest enhancement goals.
Hybrid or advanced particles	May give higher conductivity or special functions	Cost, stability, and long-term behavior remain uncertain	Promising for research, but not yet the simplest practical route.

One more point deserves attention. Many papers report performance under steady heat load. Real devices do not always work that way. They face transient load, repeated thermal cycling, and uneven heat maps. This means future studies should not only optimize average results. They should also test repeatability, aging, and local hot-spot control (Yu et al., 2024; Li et al., 2025).

A closer look at the mechanism helps explain why results differ across papers. In many studies, the first gain appears near the heated wall. The particles can alter the local thermal field and support stronger energy transport across the boundary layer. This effect is often strongest when the channel is small, the loading is modest, and the suspension remains stable. When particles cluster, the opposite may happen. The fluid can become less uniform, and the expected gain may shrink (Wang et al., 2022; Eneren et al., 2022).

Brownian motion is often mentioned in the nanofluid literature, but reviews warn against overusing it as a simple explanation. The actual mechanism may combine conductivity rise, micro-mixing, particle migration, and surface interaction. This is why one paper can report a clear gain while another finds a weak effect. The answer may not lie in one property alone. It may lie in the whole thermal-hydraulic setting of the test (Eneren et al., 2022).

The system view is equally important. Microchannel cooling is not only a heat transfer problem. It is also a flow delivery problem. A pump, manifold, seals, and channel walls must all work together. Even a moderate rise in viscosity can change the required pumping power. That can lower the real gain at device level. Ho and Chen addressed this point directly, which makes their paper especially useful for design work (Ho & Chen, 2013).

The reviewed studies also suggest that there is no single best nanofluid for every case. Alumina-water remains the most practical benchmark because it is studied often and behaves in a predictable way. Copper oxide can provide higher heat transfer in some studies, but the density and pressure loss can be less forgiving. Titanium dioxide gives a milder result, yet it may be easier to handle in some systems. The best choice depends on heat flux, channel size, pump limit, and allowable maintenance (Sivakumar et al., 2016; Moghanlou et al., 2020).

Geometry deserves separate attention. Recent reviews on electronics cooling show that the field is moving away from straight channels only. Researchers now study manifolds, wavy walls, cavities, fins, and mixed designs. These features can improve fluid mixing and reduce thermal boundary layer thickness. Yet they can also create maldistribution or higher local pressure loss. This means geometry and coolant should be designed as a pair, not as separate decisions (Yu et al., 2024; Ghani et al., 2024).

Another reason to prefer pairwise design is manufacturing reality. A geometry that performs well in simulation may be hard to machine, seal, or clean. A fluid that performs well in a small lab loop may age differently in a full system. The practical research paper, therefore, must state not only thermal results, but also fabrication route, channel tolerance, pump condition, dispersion method, and test duration. Without those details, comparison across studies stays weak (Yu et al., 2024; Eneren et al., 2022).

Table 4 Reporting items that make nanofluid microchannel papers easier to compare

Item	Why it matters	Examples of what should be reported
Nanoparticle details	Particle type and size change viscosity and conductivity	Material, mean size, shape, purity, supplier, and concentration unit
Dispersion method	Preparation strongly affects stability and repeatability	Ultrasonication time, surfactant use, pH control, and resting period
Channel geometry	Small geometric shifts can alter flow and pressure loss	Width, height, hydraulic diameter, channel count, and wall thickness
Thermal condition	Heat input controls the meaning of performance data	Heat flux, base temperature method, insulation, and sensor position
Hydraulic condition	System cost depends on more than heat transfer	Reynolds number, mass flow rate, pressure drop, and pump power
Endurance check	Short tests may miss fouling or settling	Test duration, visual inspection, post-test property check, and repeated runs

6. Research Gaps and Practical Issues

The first research gap is standard reporting. Many papers do not use the same property models, concentration units, or performance criteria. This makes direct comparison difficult. Wang et al. (2022) and Eneren et al. (2022) both show how strongly results depend on viscosity, stability, and evaluation method.

The second gap is long-term reliability. A microchannel can fail from clogging, deposition, or corrosion long before a short experiment ends. This problem is more serious in very narrow channels. Future work should include endurance testing, surface checks, and fluid re-characterization after long runs (Eneren et al., 2022).

The third gap is device-level validation. Many studies still use ideal heat blocks. That work is useful, but integrated tests are more convincing. Li et al. (2025) moved in this direction by integrating the heat sink with an IGBT device. More studies should do the same for chips, batteries, and power modules.

The fourth gap is balanced optimization. Some papers maximize heat transfer alone. Others focus only on pressure drop. A publishable design should combine both, then add stability, cost, and fabrication limits. The best future papers will likely use experiment and simulation together rather than choosing one alone (Yu et al., 2024; Li et al., 2025).

The fifth gap is the role of active assistance. A 2025 study on ultrasonic aid reported that ultrasound could reduce friction coefficient by 5.6%, reduce pressure drop by 10%, and raise heat transfer coefficient by 40.4% at 0.08 wt% nanofluid. This suggests that passive and active methods may work together, though the added system complexity must be justified (Zhang et al., 2025).

For practical engineering, a careful path seems best. Start with alumina-water in a simple geometry. Keep concentration low or moderate. Measure both thermal and hydraulic performance. Then move to geometry refinement, long-run testing, and device integration. This staged path is more credible than chasing a very large one-time thermal gain.

A final practical issue is scale-up. Many tests use short channels and controlled coolant loops. Industrial devices may use longer paths, many parallel channels, and uneven heating. Under these conditions, flow maldistribution can cancel a local nanofluid benefit. Future papers should therefore include manifold design and channel-to-channel distribution checks when possible (Yu et al., 2024).

There is also a need for better life-cycle judgment. A coolant that offers a small thermal gain but needs frequent replacement may not be a wise choice. The same is true for a fluid that requires intense mixing or costly additives. Publishable research should therefore speak to practicality as well as physics. That wider view will help the field move from promising tests to deployable cooling systems.

7. Application Outlook

The application outlook for microchannel heat sinks is broader than chip cooling alone. A 2025 review on electric vehicle components argues that microchannel heat sinks are now being assessed for IGBT traction inverters, batteries, and fuel cells. That review also notes that hybrid jet-microchannel and phase-change variants can offer superior performance in some cases. Even when nanofluids are not the only solution, they remain part of the wider design space for compact thermal control (Darbari et al., 2025).

Power electronics is a strong near-term target. The Li cavity-based study already moved toward IGBT integration. That makes the reviewed evidence more relevant to real hardware. In these devices, space is limited and hot spots are severe. A compact liquid cooler with carefully selected nanofluid may offer a useful step between simple water cooling and more complex two-phase systems (Li et al., 2025; Darbari et al., 2025).

The same logic applies to future computing devices. Recent reviews on electronics cooling stress that microchannel heat sinks remain central because they can be made small while still handling large heat flux. This matters for artificial intelligence hardware, power modules, laser electronics, and dense packaged devices. The challenge will be to deliver this performance with repeatable long-term fluid behavior (Yu et al., 2024).

From a publication view, the next high-quality papers will likely combine four elements. They will test a practical nanofluid. They will use a geometry that can actually be made. They will report hydraulic and thermal cost together. They will connect bench data to a real device class. That combination is more valuable than a paper that reports one very high heat transfer number with limited context.

For authors preparing the next round of experiments, the literature gives a fairly clear baseline. The coolant should be characterized before the run and after the run. The channel dimensions should be measured rather than assumed from design values. The pressure sensors and thermocouples should be placed so that local and average performance can both be recovered. This level of detail is not cosmetic. It decides whether another laboratory can trust and reuse the result (Wang et al., 2022; Eneren et al., 2022).

The reviewed studies also suggest a sensible order for experimentation. A researcher can first compare water and one nanofluid in a straight channel. The next step can add concentration change. After that, one geometry change can be introduced, such as a cavity, wavy wall, or serpentine path. This staged method helps separate fluid effects from geometry effects. It also makes the final paper easier to defend because each design choice can be traced to measured evidence rather than to many simultaneous changes.

There is also value in reporting null or weak results. Not every nanofluid test will show a dramatic gain. A small gain may still matter if the pressure penalty stays low. By contrast, a large gain may lose value if the system cost rises sharply. Strong publication practice should therefore welcome balanced outcomes instead of only the largest enhancement number. This would make the field more mature and more useful for engineering design (Ho & Chen, 2013; Yu et al., 2024).

So, a publishable manuscript should connect the data to an application window. A result measured at one heat flux and one Reynolds number is useful, but limited. The paper becomes much stronger when it explains where that operating window fits. It may fit compact electronics, inverter cooling, or a laboratory demonstrator. That application link helps readers judge whether the reported enhancement is truly important or only locally interesting (Darbari et al., 2025; Li et al., 2025).

Table 5 A practical experimental pathway for future nanofluid microchannel studies

Stage	Main goal	Key measurements	Why the stage matters
Baseline run	Establish water-only reference	Wall temperature, pressure drop, flow rate	Shows what the channel can do without particle effects.
Fluid comparison	Test one stable nanofluid against water	Heat transfer coefficient and pumping power	Reveals whether the nanofluid provides real system value.
Concentration sweep	Find a practical loading range	Viscosity trend, thermal gain, stability check	Prevents overuse of particles that raise hydraulic cost too much.

Geometry refinement	Study one structural change at a time	Local temperature field and pressure distribution	Separates geometric enhancement from fluid enhancement.
Endurance test	Check stability during long operation	Post-test fluid state and surface condition	Addresses fouling, settling, and repeatability.

8. Conclusion

This paper reviewed public work on heat transfer enhancement in microchannel heat sinks using nanofluids. The literature supports the use of nanofluids as a real enhancement tool, not only as a theory. Experimental studies show lower wall temperature, lower thermal resistance, and higher heat transfer coefficient in many cases. The same studies also show a recurring penalty in pressure drop, pumping power, and long-term stability risk (Chein & Chuang, 2007; Ho & Chen, 2013; Chabi et al., 2017).

The most balanced conclusion is this. Nanofluids are helpful when three conditions are met. The fluid must stay stable. The concentration must stay near a practical range. The channel geometry must be chosen with hydraulic cost in mind. If these conditions are ignored, the gain may not survive system-level evaluation (Wang et al., 2022; Eneren et al., 2022).

Among the tested options, Al2O3-water remains the safest research baseline. CuO-water can give stronger gain in some studies, but usually with higher penalty. Recent integrated and cavity-based designs show that geometry and coolant should be optimized together. That combined path looks strongest for future high heat flux cooling systems (Sivakumar et al., 2016; Li et al., 2025).

Table 6 Study matrix for the main sources used in this manuscript

Source	Type	Coolant focus	Main use in this paper
Tuckerman & Pease (1981)	Foundational experiment	Water cooling in microstructures	Historical origin of microchannel heat sink concept
Wang et al. (2022)	Review	Nanofluid properties and thermo-hydraulics	Used for property trends, viscosity penalty, and stability issues
Eneren et al. (2022)	Review	Single-phase nanofluid mechanisms	Used for mechanism debate and reliability concerns
Ho & Chen (2013)	Experiment	Al2O3-water	Used for practical performance judged with pumping power
Chabi et al. (2017)	Experiment	CuO-water	Used for quantified heat transfer gain and entrance-region insight
Li et al. (2025)	Experiment	Al2O3-water in cavity-based design	Used for modern device-level integration and geometry coupling

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