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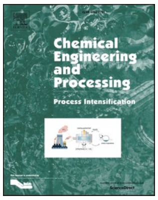

Overview of recent trends in microchannels for heat transfer and thermal management applications

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ABSTRACT

Distinctive recent research and experimental trends in microchannels for heat transfer and thermal management applications are investigated via a novel framework. The qualitative literature analysis was performed from four perspectives: materials, enhanced flow control, design, and sustainability (MEDS). The findings revealed that enhanced microchannel (MC) heat transfer performance (HTP) could be achieved by adding asymmetrical barriers, pin-fins, non-conventional geometries, mixed-wettability/biphilic surfaces, hybrid/silver nanofluids, and adopting innovative experimental and analysis methods. Additionally, researchers urged to focus on new microchannel designs and flow boiling/phase change-based experiments to understand the physics and different effects caused by various parameters. Furthermore, the qualitative analyses were transformed into quantitative results from the evaluated described methods and datasets, followed by a critical discussion of the findings. Finally, this article points out a set of promising future investigations and draws conclusions about current state-of-the-art. It is observed that, despite the decent progress made so far, microchannel-based applications still rely on traditional rectangular shapes, water-based working fluids, and numerical methods. Therefore, the role and focus on Industry 4.0 technologies to drive further innovations and sustainability in microchannel technologies are still in the early stages of adoption; this arguably acts as a barrier that prevents meeting current thermal and heat transfer needs.

1. Introduction

Consumer, industrial and digital electronic devices are now ever-present. With the emergence of Industry 4.0 and increased computational power, electronic devices are incorporated into almost all major or minor applications. Recent reports value consumer electronic markets alone at around $1 trillion; despite the COVID-19 pandemic, it is forecast to grow another 6% in 2022 [1]. Also, there has been a notable shift towards compact electronic devices; albeit, at the cost of more intense operating power and heat dissipation [2]. Thus, it can be claimed that whilst devices are increasingly and rapidly becoming portable and powerful, thermal management techniques are not efficiently catching

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Abbreviations: additive manufacturing, AM/3D; aluminium, AL; aspect ratios, AR; bare copper surface, BCS; Biphilic surface, BS; carbon nanotube, CNT; centimetres, cm; coefficient of performance, COP; commercially/pre-made, CM; complementary metal oxide semiconductor, CMOS; computational fluid dynamics, CFD; concentrated photovoltaic, CPV; copper, Cu; critical heat flux, CHF; deionised water, DW; desiccant-coated heat exchanger, (DCHE); etching, ETC; eutectic gallium-indium, EGaIn; fan-shaped cavity microchannel, FSC; film evaporation and enhanced fluid delivery system, FEEDS; further research is needed, FRIN; gallium, Ga; heat flux, HF; heat transfer coefficient, HTC; heat transfer fluid, HTF; heat transfer performance, HTP; high concentrated photovoltaic, HCPV; hybrid nanofluid/microfluids, HY; hydraulic diameter, DH; hydrogen, H/H2; indium, In; kilowatts, kW; Knudsen number, Kn; liquid organic hydrogen carriers, LOHC; lithography, Li; manifold microchannel, MMC; mass flux, MF; materials, experimental, design, sustainability, MEDS; Metres, m; Micro, μ; microchannel heat exchanger, MCHE; microchannel heat sink, MCHS; microchannel with gas cavities, MGC; microchannels, MC; micromachining, MM; micrometres, μm; moisture transfer coefficient, MTC; multi-layered microchannel, MLM; nitrogen, N2; numerical method, NM; other analysis methods, OAM; other fabrication method, OFM; other materials, OMT; other working fluids, OWF; oxide, O/O2/O3; phase change materials, PCM; polydimethylsiloxane, PDMS; polymethyl methacrylate, PMMA; porous wall, PW; research question, RQ; Reynolds number, Re; silicon, Si; silver, Ag; tantalum, TA; test surfaces, TS; thermal conductivity, K; thermo-electric power generator, TEG; three dimensional, 3D; titanium, Ti; uncertainty analysis, UA; water-mixture, WM; watts, W; working fluid, WF; zinc, Zn; Z-score, z.

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up at the same rate. Therefore, continuous improvement and solutions via technology are warranted to lead to further innovations.

Aligning with current industry trends and the need to adopt sustainable approaches, microchannels (MC) present innovative commercialisation possibilities to tackle thermal management issues in modern electronics. The earliest MC heat sink (MCHS) technology can perhaps be credited to Tuckerman and Pease [3]. IBM's high-performance computer chip production in the 1980s gave rise to challenges related to effective heat dissipation. In response, the works of Tuckerman and Pease highlighted an innovative approach via scaling down conventional heat sink dimensions to a micro-scale to gain significantly improved heat removal performances [3]. In the subsequent decades, researchers have attempted various investigations of diverse MCHS improvements and applications.

MC can be defined as channels that fall in the spectrum of microtechnology or microscale, i.e., technology or items possessing geometrical features in the range of micrometres [4]. Hydraulic Diameter (DH) is an important parameter when working with flows in non-circular tubes and channels. Hence, numerous authors have typically classified MC as having a DH under one millimetre. In microchannel flows, DH can be measured by dividing the cross-section flow area against the wetted perimeter (all surfaces where fluids exert shear stress) of the cross section [5].

Although MC were initially presented for the computing/electronics sector, modern-day MC are utilised extensively in pharmaceutical and biochemical, automotive and aerospace, and energy production, amongst many other industries [6]. The primary advantages of MC lie in their compactness, heat exchange capacity, and cost-effectiveness. Nevertheless, technologies, experimental methods, and manufacturing tools are constantly improving. Consequently, there are massive scopes for MC performance improvements to cope with the thermal management challenges triggered by rapid electronic miniaturisation. Therefore, it is imperative to obtain a holistic overview of the current research trends, experimental methods, and analysis related to MC; this will not only help identify research gaps but also recommend areas for further advancements.

This article aims to perform a systematic investigation of recent developments and trends related to MC applications, with a focus on heat transfer and thermal management. The main experimental setups, research, and technologies associated with MC are highlighted and critically appraised. Additionally, scopes for further developments and inquiries have been determined. This article attempts to answer the following research questions (RQ):

1. **RQ1:** What are the key research themes and sub-themes identified and discussed by recent literature studying heat transfer/thermal management in MC?
2. **RQ2:** What are the gaps in the extant literature and future scopes (FRIN) for studying MC for heat transfer/thermal management purposes?
3. **RQ3:** Which experimental trends have been observed from recent literature to study heat transfer/thermal management in MC?

The article is structured around the research questions and segmented into sections. Section 2 sheds light on the review methodology that aided in shaping this paper. Section 3 caters for the research questions and key recent developments of MC, evaluates available methods, experiments, and identifies gaps for future research scopes. The concluding sections deal with the discussion, conclusion, and recommendations for future work.

2. Methodology

The methodology for this review paper is mainly dependant on descriptive and exploratory analysis, qualitative data, and findings from extant literature; this data was, in turn, converted into quantitative results and graphs to analyse and identify possible research gaps and trends within recent MC experimental investigations. Scanning the extant literature helped form the initial baseline for this paper. Hence, a mixture of databases was explored; these include Google Scholar, OpenAthens, Shibboleth, and related journals such as Elsevier, Emerald, IEEE, SAGE, and Springer.

Also, the methodology of this article was inspired and adapted from the work of [2,7–9]. The extant research has reviewed MC technologies focusing on electronic cooling [2], configurations and patents [7], heat sink applications [8], and modelling strategies [9]. Therefore, this article adapts from previous work and combines various aspects to produce a more diverse and holistic overview of current research levels, status, and trends in MC heat transfer and thermal management applications. Furthermore, this article's methodology also aligns with the vision of tackling smaller issues to lead to wider technological and continuous improvement [10]. Moreover, numerous authors have contended that combining different techniques, strategies, and mixed methods can lead to better results [11]. The search methodology followed a funnelling process where broad keyword variations were used to maximise the chance to identify relevant research articles. The authors were mindful of previous studies suggesting methods based on the relevance, publishers, year, industries, etc. Acknowledging these suggestions, the inclusion criteria for this literature review were peer-reviewed journal papers, titles or abstracts containing any variations of the used keywords related to MC experiments and investigations. Also, the initial search mainly focused on research papers dating from 2017 to 2021; a five year timeline has also been recently followed by [9] for their review. Furthermore, being mindful of the ever-decreasing product development times [12,13]. The five-year range was selected to be more up-to-date with modern industrial and technological practices and to develop research questions aligned with current scopes.

Initially, all MC applications were taken as the whole population data. Afterwards, topics focused more on heat transfer areas such as cooling, mixing, flow boiling and other related research areas. Therefore, in this paper, 70 research papers were appraised in terms of the experimental methods, area of interest and impact, and recommendations for future investigations. Furthermore, the qualitative findings were categorised into a newly formed Materials, Enhanced Flow Control, Design, Sustainability (MEDS) framework consisting of four primary perspectives. These were material usage, experimental methods, design, and sustainability elements. The MEDS framework helped to systematically narrow down areas to assess where the possible research gaps could be. In articles where a topic overlapped into more than one perspective, qualitative emphasis was given to experimental methods and research recommendations to categorise the literature.

A sample of 100 papers was considered an ideal number to appraise the current state-of-the-art literature. However, not all research papers were suitable for selection as they lacked the necessary depth or were unaligned with the analysis needs for this paper. Also, based on the initial keyword and inclusion criteria, the searches on Google Scholar showed around 17,500 potential research articles for appraisal. Therefore, considering this as the target population, a sample size of 68 was deemed sufficient for making statistical inferences at a 90% confidence level and 10% margin for error. A combination of suggestions made by Farrell [14] and SurveyMonkey calculator [15] assisted in identifying the chosen sample size. Moreover, numerous authors have debated that there is no universal/general rule for convenience sampling. In addition, Fellows and Liu [16] have indicated that a sample size of 30 can be deemed acceptable for making statistical analysis and inferences. Thus, based on the calculations and previous work, a sample size of 70 was arguably sufficient to assess current literature trends. The following equation, adapted from [14,15], was used to calculate the sample size to make statistical analyses:

$$Sample\ size = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1 + \left(\frac{z^2 \times p(1-p)}{e^2 N}\right)}$$

where N = population size (17,500);
p = population proportion (assumed 50% in this case);
z = z-score (1.65);
e = margin of error (10% or 0.1).

3. Literature review

3.1. Material perspective

3.1.1. Working fluids

The utilisation of different working fluids (WF) for MC during multiphase flow has been explored using hydrophobic sunflower oil and water as working fluids. To illustrate, Chiriac et al. [17] monitored multiphase flows in MC using two immiscible fluids. The flow visualisation and μPIV (micro Particle Image Velocimetry) measurements validated numerical results qualitatively and quantitatively. For future research, quantitative exploration of the influence of material properties' ratios and applying similar methods with non-Newtonian fluids with high viscosity were advised.

Additionally, Hoang et al. [18] performed an experimental investigation with a two-phase cooling heat sink using a hydrophobic dielectric (Novec/HFE-7000) WF. The heat transfer coefficient (HTC) increased with the flow rate in the single-phase and convective boiling region; in the nucleate boiling region, HTC increased notably with heat flux (HF). This increasing trend of HTC with HF was attributed to the refrigerant properties. Compared to water, the WF has lower surface tension and contact angle that generated bubbles with smaller departure diameters; thus, the refrigerants WF experienced nucleate boiling over a greater MC length and produced a positive trend of HTC with HF [19]. Also, HTC improved with reduced subcooling in the heat sink, at the cost of increased pressure drop. Thus, the coefficient of performance (COP) is primarily dependant on subcooling in two-phase. Fin height reduction produced better thermal performance until the optimum point due to a higher fluid penetrating factor. The experimental findings can be related to Novec type WF and utilised for a range of features: HFs, subcooling, Reynolds numbers, and DH.

Similarly, Dalkılıç et al. [20] analysed HTC and critical HFs of R134a (generally hydrophobic) in two-phase flows. The results showed that raised vapour quality at constant inlet saturation temperature decreases both CHF and HTC. At constant inlet vapour quality, the CHF decreased, and HTC increased with inlet saturation temperature. Nevertheless, a relatively higher temperature difference is required to reach the CHF at reduced temperatures than high inlet saturation temperatures.

Guo et al. [21] researched pressurised filling processes of two working fluids in a porous closed-loop MC; the theoretical presumptions agreed with the experimental results. They were successful in generating acoustic waves via hydrophobic eutectic gallium-indium (EGaIn) compound usage in MC. For future work, feasibility of self-aligned comb--shaped single-electrode interdigital transducer (IDT) adoption in the industry was suggested.

Alternatively, Abdulbari et al. [22] employed a hydrophilic Xanthan gum as a drag-reduction (DR) agent for flow assessment in MC. The solution exhibited non-Newtonian behaviour due to increased viscosity from increasing concentration. The %DR increased by raising additive concentration, length of MC, and decreasing the width. Future research could involve advanced flow visualisation techniques with polymer molecular weight effect on DR.

3.1.2. Nanofluids/nanoparticles

Experimental investigations with nanofluid/nanoparticle utilisation are another promising research area. Nanofluids are insoluble particle-suspensions using solid materials (within the average size of 0–100 nm) [23]. Compared to pure liquids or water, high nanofluids concentrations have been reported to show better thermal stability [24]; they can also provide improved cooling solutions and HTC [25,26]. Martinez et al. [27] developed an experimental methodology that allows for studying Titanium dioxide (TiO2)-H2O-based nanofluids as coolants in MCHS. Nanoparticle dispersion increased the thermal conductivity (K) of the base fluid within the examined temperature. Furthermore, incorporating nanoparticles into the water can improve heat dissipation in MCHS for the studied concentration range. The optimum thermal energy gain was shown by MC cooled with the nanofluid having a concentration of 1wt% and Re = 200. As a result, a more suitable MCHS nanofluid arrangement can be studied for subsequent research.

Also, Ding et al. [28] appraised the effect of TiO2-H2O nanofluids in thermal energy storage (TES) MC to enhance the thermal conductivity (K) of phase change materials (PCM). TiO2-H2O nanofluids having 0.5 wt%, 0.7 wt%, and 1.0 wt% can increase Nusselt number in the melting and solidification process. TiO2-H2O nanofluids addition results in increased pressure drop (<9%). Therefore, more applications of TiO2-H2O could be investigated.

Sarafraz and Arjomandi [29] explored the potential usage of liquid metal for HF transfer for next-generation solar thermal energy receivers. Liquid Gallium (Ga) showed superior thermal diffusion, conductivity, improved HTC, and heat transfer rate compared to water. Similarly, nanoparticles augmented HTC due to the internal thermal conductivity of AL2O3, and the Brownian motion of Ga nanoparticles. The pressure drop penalties were significantly higher for Ga nano- suspensions and pure Ga compared to water. Thus, the application of Ga suspensions for high HF applications with reduced pressure drops needs assessment.

In a separate study, Sarafraz and Arjomandi [23] investigated low HF conditions using an MCHS for thermal and pressure drop performances; the nanofluid used was copper-oxide/indium (CuO/In). Higher HTC was observed for increased HF, peristaltic mass flow, and mass concentrations of over 8%. A high-pressure drop penalty was present for the liquid Indium nanofluid at a mass concentration of over 8%. Thus, the adoption of CuO/In nanofluids application with reduced pressure drop penalties needs analysis.

In another investigation, Sarafraz et al. [30] assessed the thermal performance of MCHS in laminar flow. Silver (Ag) nanofluids improved HTC but at the cost of increased pressure drop, thermal resistance, and friction factor. Hence, the feasibility of adoption of Ag/water nanofluids with reduced friction factor and pressure drops in the micro-electric cooling application needs further exploration.

Sarafraz et al. [31] also studied thermal performance and fouling inside a MCHS but using a carbon-nanotube (CNT)-water nanofluid. The nanofluid produced a higher HTC and reduced temperature profile compared to water. The results also indicated that nanofluid flow rate and mass highly increase HTC. Also, increasing mass concentration reduced the operating time to reach uniform fouling thermal resistance, but overall thermal resistance decreased with increasing nanofluid concentration. As a result, CNT usage requires further investigation related to friction factors and pressure drop penalty.

On a different take, Simsek et al. [32] experimented with complementary metal oxide semiconductor (CMOS)-compatible monolithic MCHS convection heat transfer and pressure drop using Ag nanowire suspension. Silver nanofluids showed the highest HTC amongst the examined working fluids, but all had similar hydrodynamic performance. A 56% increased HTC is possible without added pumping power. Thus, the adoption of silver nanowire suspension shows promise for heat transfer improvements.

3.1.3. Surface treatment/manipulation

The extant literature also indicates possibilities through surface manipulation using various materials to reach desired effects. Ahmadi et al. [33] conducted flow boiling experiments on wholly hydrophobic and three mixed wettability surfaces for a high aspect ratio (AR) MC. The biphilic surfaces (BS) performed better than the wholly hydrophobic surface. Additionally, BS provided vapour breakup, enhanced flow boiling heat transfer, and reduced the time of bubbly flow regime; however, they extended the slug flow regime. Hence, BS for high HF cooling can be examined.

Zhang et al. [34] investigated surface wettability by studying boiling heat transfer features on 3D heterogeneous surfaces with diverse wettability. The highest HTC was found in test surface three (TS3), over six times compared to a bare 2D surface (BCS). The BCS consisted of a bare copper surface polished with 5000-grit sandpaper having a water droplet contact angle of 88.6°, while the TS3 was a fluoridized copper oxide surface with a contact angle of 156.1° — meaning a hydrophobic/superhydrophobic surface having no affinity to water [35]. However, the highest CHF was in TS2, over 60% than BCS. The TS2, on the other hand, was made via thermally oxidising the BCS at 400 °C to produce an oxidized copper layer with a contact angle of 8.6° — meaning a hydrophilic surface [35]. Consequently, the synergistic wettability effects and microstructures were linked to producing oblate and conical bubble growth patterns. This research provided a guideline for further MC developments with different wettability exhibiting hydrophobic and hydrophilic characteristics.

Yin et al. [36] examined the chemical absorption effects on the formation of dynamic characteristics and preliminary length of Taylor bubbles. The results highlighted that the absorption process causes gas dynamic pressure drop reduction and increased expansion stage time in the overall bubble formation process. Therefore, chemical absorption on bubble formation in MCHS can help lead to novel designs.

On the other hand, Venegas et al. [37] evaluated a membrane-based micro-desorber design, working via low heating temperatures. The hot water temperature had a direct relationship with desorption rate, solution temperature and partial pressure to improve the desorption process. Also, increasing the flow rate resulted in a minor reduction of effective desorption surface; thus, it is possible that an extended length may be used to reach initial desorption temperatures.

Jayaramu et al. [38] performed a comparative assessment of surface characteristics on flow boiling heat transfer and pressure in an MCHS using three cases: Case-1 was a freshly machined surface; Case-2 was an aged Case-1 channel surface after multiple experimentations; Case-3 was the same aged surface but cleaned using 0.1 M hydrochloric acid. Case-2 performed the worst due to increased wettability and thermal oxidation of the heating surface resulting from the repeated experiments; Case-3 performed the best due to increased nucleation site density, but pressure drop changes are minimal. Accordingly, other material surfaces for flow boiling in MCHS are a good topic for further research.

Surfactant usage is also an exciting area of research. Roumpea et al. [39] investigated droplet formation in an organic continuous phase within a MC having surfactants. Surfactant's additions reduced squeezing and dripping regime areas but increased the jetting and threading regime areas. In comparison, surfactant-free solutions produced bigger and lower tip-curvature drops. Mean velocities showed that surfactant improved the local velocity difference between two-phase flows. Therefore, studying the dynamics and effects of droplet formation with various surfactants is worthwhile.

Moreover, Liang et al. [40], under condensation conditions, investigated heat and moisture transfer characteristics of desiccant-coated heat exchanger (DCHE) and MCHE. The experiments revealed that the temperature of hot water correlates positively with dehumidification but negatively with heat recovery. It was equally found that high inlet air velocity improves heat transfer while desiccant coating hampers it. Furthermore, the pressure drop increases with airspeed; an increase in cooling water temperature shows a minor reduction in the pressure drop, but the hot water temperature exerts minimal effects.

3.1.4. *Manufacturing techniques*

The availability of different manufacturing possibilities presents new development opportunities. Zhang et al. [41] experimented with 3D-printed manifold MCHS with Inconel 718 for high heat aerospace purposes. The new design exhibited 25% improved heat transfer density at a coefficient of performance (COP) of 62. The authors associated the heat transfer density improvement with size optimisation whilst minimising the mass of the plate-fin heat exchangers. The plate-fin heat exchangers sizing was gained by fixing the mass flow rate and COP to match the core design of a manifold-MCHE. Furthermore, the researchers reported that the additively manufactured design improved HTC due to two key factors, high area-to-volume ratio and manifold-MCHE-inspired strategy that showed heat transfer enhancement in earlier studies. However, in terms of pressure drop, it displayed an expected trend where the pressure drop increased with increasing Reynolds number. Moreover, additive manufacturing could produce a fin thickness as low as 0.18 mm. Therefore, further 3D printed manifold investigations could be a worthwhile area for future investigations.

Yameen et al. [42] studied heat transfer properties of an additively manufactured metal MCHE with complex interior designs — the smallest length produced was 0.48 mm. Thus, more 3D design manifolds can be further examined.

Moreover, Bae et al. [43] presented results of a two-phase, embedded cooling system for high HF electronics. Lower pressure drops and improved HTC were expected for higher ARs in SiC MC fabrication. Future research could cater to the following topics: thinner test chips (200 μm) with deeper SiC trenches for overall thermal resistance reduction and improved fin performance; detailed clogging assessment to prevent MC clogging; thermoelectric cooler into the thin-Film Evaporation and Enhanced fluid Delivery System (FEEDS) Manifold-Microchannel (MMC) system for 5 kW/cm2 hotspot cooling.

3.2. *Enhanced flow control perspective*

3.2.1. *Flow boiling*

Flow boiling optimisation is arguably one of the most sought-after research areas for MC-based applications [44]. Flow boiling is a phenomenon that is caused when fluids move across a heated surface via external means or the naturally occurring buoyancy effect [45]. It is one type of flow where a phase change can occur and is characterised by a continuous two-phase flow of liquid and vapour [46]. However, due to the multiple dependencies and complex mechanism behind flow boiling, researchers may sometimes focus on the general heat transfer behaviour during flow boiling rather than the bubble dynamics or phase change regimes [45,17].

Wang et al. [47] monitored the effects of refrigerant properties, mass flux (MF) and saturation temperature on the flow boiling friction pressure drop. The results show that increasing mass flux and reducing saturation temperature both have a positive effect on the two-phase friction pressure drop. Increasing mass flux leads to an increased two-phase friction pressure drop mainly due to the increasing liquid-vapour shear forces and partially from the liquid-solid shear forces. Additionally, two-phase friction pressure drop increases from a reduction in the saturation temperature because decreasing the saturation temperature causes enlarged liquid-vapour velocity differences and increased liquid viscosity. Compared to single-side heating, heating from both sides lead to greater two-phase friction pressure drops in MC arrays. Subsequent studies can focus on new empirical methods designed using experimental data that predicts data with high accuracy and a lower margin for error.

Panda et al. [48] experimented with two-phase refrigerant maldistribution in the inlet headers of microchannel heat exchangers (MCHE). The Loop header exhibited superior distribution performance. They also provided a comprehensive simulation approach for the MCHS header maldistribution problem. Future investigations can cater to developing a full-scale heat exchanger simulation model with air-side calculations, condensate drainage, flow boiling in MCHS, flow expansion in the expander valve, and the dynamics of oil and refrigerant inside the compressor.

Xia et al. [49] researched the technique to reduce continuous flow boiling instability with intermittently moving gas-liquid interface that may potentially trigger pressure drop and wall temperature oscillations — leading to flow control issues and security risks. They proposed straight and triangular ridged MCs using multiple sensors setup. A prediction model highlighted that raising inlet flow restriction, reducing inlet temperature and HTC can reduce flow boiling instability significantly, along with unstable boundary slopes.

On a different take, Jia et al. [50] compared flow boiling between novel and traditional rectangular designs with increasing HF from single-phase to CHF. The Porous wall (PW) MC improved onset nucleate boiling, CHF, enhanced heat transfer, pressure drop reduction, and two-phase flow instabilities. Additionally, The PW design contained nucleation sites and pin-fins provided wicking effects.

Lin et al. [51] numerically investigated single bubble growth via developing a custom solver using the VOF method and Hardt's phase-change model. The results showed flow reversal suppression with increased MF but at the cost of reduced flow boiling enhancement. Finned-microchannels provided around 40% less thermal resistance and minimal flow reversal compared to a micro gap-microchannel setup. Therefore, further experiments to enhance flow boiling in similar setups need appraisal.

Oudebrouckx et al. [52] presented an innovative prototype system to measure thermal conductivity (K) under flow conditions via Transient Thermal Offset (TTO) method. Flow rate can be calculated if K and the specific linear calibration curve for a liquid with this value are known. Absolute K values under continuous flow can be determined if flow rate and the exponential calibration curves are given. Therefore, the viability of a combined single system for flow rate measurement and monitoring during flow boiling applications could be explored.

3.2.2. *Phase change flow patterns*

Phase change phenomena is another vital element related to MC-based technologies. The term phase change is a broader term that can refer to the transition of one state or phase of matter to another; for instance, solid to liquid, liquid to gas, gas to liquid, or even gas to plasma. Phase changes usually have technical terms such as melting, freezing, condensation, and boiling, amongst many others [53]. Whilst Section 3.2.1 deals mainly with general heat transfer and flow control aspects of flow boiling and two-phase flow. Section 3.2.2 caters for the flow regime, patterns, and bubble dynamics. The phase change during flow boiling/condensation changes the volume, crystalline structure, and frictional resistance of the fluid. Therefore, as the literature indicates, these phase changes impact the HTC, shear forces, and velocity in the liquid-vapour flow regimes, which in turn, affect the heat transfer of the overall system.

Matin and Moghaddam [54] studied elongated bubbles and wavy-annular regime transitions during flow boiling in rectangular MC with varying aspect ratios. The wavy-annular flow transitions are linked to the thickening of the liquid film and a drastic increase in the vapour velocity; this drastic change makes the interface go into unstable (wavy) transitions. Low vapour velocities resulted in a transition to annular flow with increased channel height (reduced aspect ratio). Therefore, critical shear stress at the vapour-liquid interface was suggested.

Furthermore, Lei, et al. [55] investigated the effects of dispersed phase viscosities, continuous phase viscosities, and two-phase flow parameters on droplet length. The dominating factors for flows in annular, slug, droplet, and jet regimes are inertia, interfacial tension, shear, and shear and drag forces, respectively. Viscosity fluctuations in the dispersed phase affect flow pattern transition processes of annular flow to slug flow and slug flow to droplet flow; however, it has minimal effect on slug properties and droplet length. Prediction scaling laws were proposed for the slug and droplet lengths formed by different flow patterns.

Another important investigation was presented by Ronshin and Chinnov [56] who determined a novel method for regime boundaries and for appraising the two-phase flow patterns. Transitions from one regime to another can be done as follows: jet to bubble - increasing bubble formation frequency and liquid's superficial speed; jet to a stratified - massive increase in the film region's lower walls and raising superficial gas speed; stratified to annular - greatly increasing the film area's upper wall via an increase in the superficial liquid's speed; bubble to the churn – destroying horizontal liquid bridges and, thus, reducing the frequency of bubble formation via increasing the gas velocity.

Slug generation and control during phase change can also lead to improved thermal management and heat transfer. Qian et al. [57] investigated dynamic dispersed phase injection flow rate effects on slug generation. The experiments to observe dynamic disperse flow rate showed rectangular waves most affected the slug size. Also, the triangle wave affected the separation distance and the slug generation time comparatively more.

Zhang et al. [58] appraised hydrophobic MC with flow condensation of varying ethanol-water mixtures. The flow condensation was highly dependant on the hydrophobic surface; ethanol concentration increase resulted in slug/bubble flow and no droplet condensation.

Similarly, Kovalev et al. [59] experimented with a liquid-liquid setup with a very low viscosity ratio. The research findings contradicted extant experimental findings for low plug velocity. Thus, the proposed usage of experimental values for classifying different plug patterns needs further analysis.

3.2.3. *Flow resistance*

The reduction of flow has been the key to the implementation of heat transfer at microscales. Microscale can be defined as a scale for items at the micrometre level, generally used to describe very small or microscopic items ranging anything from 1 to 100 μm [4]. Kravtsova et al. [60] investigated three flow regimes and the resistance effects of external periodic perturbation on flow regime distribution. The average downstream flow velocity changed from a parabolic curve to a three-pick curve, and then, showed a uniform zone after passing the Dean vortex. For the stationary asymmetric flow regime, 33% growth of mixing efficiency was obtained.

Garg and Agrawal [61] presented two different investigations related to inflow frictional resistance. Inflow frictional resistance is generally one the biggest contributor to the total resistance of a flow, and it is dependant on the wetted surface and surface roughness [62]. Initially, they measured pressure and temperature in a three-dimensional MC, consisting of planned roughness of varying lengths for gaseous slip flow regimes. Limited penetration for streamlines inside micro-ridges produces reduced contact of slipping gas molecules with the wall surface but increased Re. Therefore, experiments at higher Knudsen numbers could be done to observe gas rarefaction effects on the choking point of the micro-ridges. Also, different orientations and shapes of ridges can be investigated as per the application.

In their second experiment, Garg and Agrawal [63] investigated the effect of adiabatic subsonic choking on frictional resistance for three-dimensional MC in a rarefied gas regime. The choked state of the 3D-MC was noted to be more adiabatic than isothermal. The findings also highlight conditions for AR, Reynolds number and Knudsen number where significant expansion loss might occur in a MC slip flow. Future research can study the effects of high Re on highly rarefied choked gas flows at high Knudsen numbers. The Knudsen number (Kn) is a dimensionless parameter that characterises the flow's boundary conditions. Kn can be defined by the ratio of the average free path to the average pore diameter [53].

Wang et al. [64] investigated liquid pumping in MC via surface acoustic wave and heat expansion forces. The results showed that a thinner MC (250 μm compared to 500 μm) design with a hydrophobic Cytop surface boosted pumping velocity by over 130% for experiments with constant liquid volume with identical applied input power. Therefore, there is potential for this technique to be applied in small-scale liquid control and deliveries. Moreover, a similar setup for two-phase flow and pressure drop appraisal can be explored.

Lastly, Ji et al. [65] examined an oil-water mixture emulsification process for flow pattern characterisation having a wide range of Re. High turbulent flow leads to finer and increased monodispersed droplets in the emulsion. In mid- range Re numbers, a high oil volume ratio exhibits laminar flow; this is more noticeable in the 600-300 setup. Analysing droplet mean diameter and polydispersity index, unequal configuration produced swirl flow and greater performance than equal size setup for high Re. The 600-300 impingement setup could have potential industrial applications for emulsions at high flow rates. Therefore, future studies should focus on drop deformations/breakup details in MC.

3.2.4. *Thermal resistance*

Reduction of thermal resistance is another area where research has been done. Al Siyabi et al. [66]. examined the application of a multilayered-microchannel (MLM) heat sink in the high concentrated photovoltaic (HCPV). The results showed that using MCHS with 3-layers increased electrical power; temperature reduction had been detected in the solar cell when the number of layers increased from 1 to 3 for the identical flow rate. Also, the module performed with a better electrical performance outdoor than indoors.

On a different take, Al Siyabi et al. [67] employed multi-layered MCHS for concentrating photovoltaic cooling. The number of layers was inversely proportional to heat sink thermal resistance and heat source maximum temperature. Thermal efficiency significantly improved due to the heat transfer fluid (HTF) outlet temperature when the number of layers increased from one to three. Moreover, the heat sink could adapt to a range of power ratings with small changes in the thermal resistance. Nevertheless, further research is needed to employ MLM heat sinks in a single solar cell CPV module, including both the electrical and thermal performance appraisal using the indoor and outdoor classifications.

Zhai et al. [68] designed and verified a theoretical model to predict flow and heat transfer in MCHS. Convective thermal resistance is an important factor and should be reduced. Furthermore, to minimise entrance effects, the length of the entry channel needs to be raised to gain uniform flow distribution. Therefore, similar theoretical frameworks can further aid to improve future MCHS designs.

3.3. *Design perspective*

3.3.1. *Aspect ratios*

Aspect ratio is defined by the ratio of its different dimension sizes, usually using the largest against the smallest dimensions [69]; in the case of rectangular ducts/channels, it is found by dividing the width by height. Numerous authors have indicated the need to further research for improved clarity on the effects of aspect ratios. Consequently, Özdemir et al. [70] appraised the results of the flow boiling of water in a single rectangular MC with identical hydraulic diameters (DH). Bubbly flows were not seen for the smallest AR (0.5) at the outlet. The HTC showed a negative relationship with the channel AR until HF values reached around 480–500 kW/m^2. Channel ARs had a negligible effect on the HTC for higher HF. The researchers recommended further research regarding the effect of AR for clarity. Nevertheless, they gave a possible explanation for their findings. For their design, at lower ARs (deep channels), the heat transfer was better due to higher buoyancy effects and a thicker bottom-wetted surface. Alternatively, at higher HFs, the nucleate boiling regions were perhaps replaced with film evaporation regions, making the effect of ARs negligible.

Luo et al. [71] studied hydrodynamics and heat transfer performance (HTP) of annular flow boiling in a high width-to-depth ratio MC. The experiments showed that increased wall HF or inlet quality decreases the thickness of liquid thin film between the interface and the heating wall; thinner liquid films lead to larger local HTC, lower wall temperature, and improved HTP. Nevertheless, the downside of increasing the inlet mass flux is that it decreases the wall's HTC.

Li et al. [72] produced investigations related to aspect ratios in MC. They studied subcooled flow boiling in a high-aspect-ratio, single-side heated MC for varied alignments on hydrophilic and super-hydrophilic surfaces. The findings indicated that, in low mass fluxes, vertical downflow exhibits the highest pressure drop; maximum pressure drop was gained for high mass fluxes during bottom-heated horizontal flow. Also, dominating inertial forces weaken the effect of orientation; the impact of surface wettability is more prevalent for horizontal configuration at a given HF. Consequently, optimised flow orientation and surface wettability for MCHS at different aspect ratios can be further studied.

On a separate occasion, Li et al. [73] experimentally evaluated saturated flow boiling in a single-side-heated vertical narrow MC. All experimental conditions show annular flow patterns and convective evaporation dominated the heat transfer system; thinner liquid film provided increased HTC. Furthermore, the local dry-out phenomenon occurred on the untreated hydrophilic surface, but the super-hydrophilic part kept the liquid film uniform and prevented the phenomenon. The authors suggested modified correlation formula to calculate the HTC of saturated flow boiling in a vertical narrow AR single-sided heating MC.

Aspect ratios have also been studied by Duryodhan et al. [74] to assess mixing in spiral MC designs. They visualised homogeneous mixing at a low (0.36) and high (1.2) AR at various angles but having the same Re. Their qualitative analysis of the flow mixing revealed that the spiral MC with higher AR provided comparatively better homogeneous mixing efficiency, but optimum Re and AR balance need consideration. Therefore, ensuing investigations could cater to developing optimised designs for spiral MC designs with superior efficacy.

Again, a similar investigation utilising high AR was performed by Yin et al. [75], where they analysed water flow boiling using a large AR MC. They found that nucleate boiling is prevalent in large AR, and HTC is dependant on MF. Moreover, HTC for sweeping and churn flow are larger comparatively. The strengthening bubble confinement effect was not observed in large AR MC. Hence, the feasibility elements of large AR MCs can lead to further research.

3.3.2. *Geometry/shape manipulation*

Achieving the desired performance through changing geometries is probably the most followed technique to reach the desired HTP in MC. For instance, Abdo et al. [76] determined the optimum configuration for integrated MCHS in CPV (hybrid concentrator photovoltaic)-TEG (thermoelectric power generator) combined system; this caused a minimal effect on the system performance. However, the new design achieved reduced mean solar cell temperatures and higher performances than the previous design. They suggested design improvements via a TEG with greater conversion efficiency and a more effective heat sink to minimise heat release from the TEG side.

Ringkai et al. [77] studied characteristics of water-in-oil droplets at the interfacial surface in an offset T-junction MC — with different radii. They noted that minor increases in the channel size produce a significant increase in the overall liquid flow. Likewise, increasing the radius of the offset MC increases the cross-sectional area but decreases distilled water phase's velocity. Lastly, droplet sizes increased with radius and were approximately equal to the width of the MC.

Vinoth and Sachuthananthan [78] compared heat transfer and flow characteristics of an oblique finned MCHS having pentagonal and triangular cross-sections. The pentagonal MCHS shows better characteristics in heat transfer, thermal resistance, flow characteristics, and pressure drop than the triangular design. In addition, the mixing of nanoparticles ($Al2O3 + CuO$) to the working fluid revealed a greater heat transfer rate than a single nanofluid.

Hou and Chen [79] designed and simulated MCHE with three re-entrant cavity shapes (circular, trapezoidal, and rectangular). The findings pointed that increased flow rate leads to higher pressure drops in the MCHEs; rectangular shape had the most pressure drop and Darcy friction coefficients. Similarly, increased flow rate leads to a gradual increase of hot water temperature in MCHE; circular shapes have the lowest hot water temperature, followed by trapezoidal and rectangular shapes. Moreover, circular re-entrant cavities based MCHE had the highest combined performance at the examined Reynolds number. Accordingly, subsequent investigations could assess other re-entrant cavity shapes to achieve the optimised design and features.

Ye et al. [80] evaluated cross junction MC having gas cavities (MGC) to overcome mass transfer issues in Taylor flow. The results showed MGC bubble shapes being more sensitive to the capillary number due to thicker liquid film and a sharper bubble shape for given conditions; this produces a larger surface area. Also, velocity slip and radial fluctuations at the gas cavity interface notably enhanced liquid transport. Thus, mass transfer in MGC needs further appraisal via manipulating liquid film surfaces.

Nadaraja et al. [81] studied multilayer MC arrangement and its effect on the thermal-hydraulic performance of MC arrays. They found that thermal-hydraulic performance obtained in the two-layer MCHS is lesser compared to single-layer MCHS, going against extant literature findings. The abnormal deviation could be due to manufacturing limitations and heat losses in two-layer MCHS. As a result, further investigation could be done on solving heat loss problems, improving manufacturing precision, and the effects of additional layers on the thermal-hydraulic performance of MCHS.

Li et al. [82] designed and examined MCHS with triangular cavities at sidewalls. The new design performed better than the traditional designs, enlarged heat transfer area, developed liquid film formation, nucleation intensity and bubble departures, HTC, and lowered pressure drops. Thus, the new design showed promising results for efficient microelectronic cooling.

Vinoth and Senthil [83] evaluated the influence of channel geometries of three oblique finned MCHS to study heat transfer and hydrodynamic features. Out of the three shapes — semi-circular, square, and trapezoidal — the trapezoidal cross-section provided better heat transfer for electronic cooling systems. Therefore, more cross-section geometries can be investigated for future research.

Walunj and Satyabhama [84] examined three designs for low HF applications. Results showed transitioning from rectangular to parabolic and steeped geometries improved heat transfer, HTC, and reduced incipient temperature.

3.3.3. Barriers/restrictions

Previous research has shown positive implications when implementing barriers/restrictors to enhance flow boiling, heat transfer, and mixing. Haghighinia et al. [85] experimentally and numerically explored two different designs having symmetric and asymmetric patterns of circular barriers. The results show that repetitive ‘split and recombine’ produced irregular motions and improved mixing. At bents, folding is the key factor to increase the inter-material area. Additionally, increasing Reynolds number led to an increase in mixing efficiency in separate parts.

Alternatively, Oudah et al. [86] investigated the effects of different inlet restrictors (IRs) configurations on the thermal-hydraulic performance of flow boiling in an MCHS. All IRs enhanced the CHF performance of the MCHS flow boiling; however, the 5IRs setup worked best at low mass flux, whereas the 1IR case works best at high mass flux. It was also noted that IRs decrease the HTC at low mass flux, increase the HTC at high mass flux and HF, and exhibit higher pressure drop penalties in all cases. Consequently, optimum MC dimensions with IRs should be explored depending on the operational parameters (mass/HF) of the MCHS.

Also, Kumar [87] analysed the impacts of rectangular and semi-circular type MC grooves using the finite volume method. It was noted that trapezoidal channels provide 12% more heat transfers; the semi-circular grooves show 16% more heat transfer over rectangular grooves in the trapezoidal MC. In addition, for trapezoidal MC, groove width is more important than channel height.

Moreover, Ma et al. [88] explored optimised MCHS with offset zigzag cavities for enhanced flow boiling. The nucleate boiling area near the inlet showed severe instability, and flow reversal strength improved with low HF. However, increasing flux generated steam that reduced fluctuations. Moreover, zigzag MC raised heat transfer characteristics having lower wall temperature at onset nuclear boiling, HTC, CHF, and enhanced flow boiling stability by restricting flow reversal and pressure drops. Accordingly, MC with other configurations for flow boiling studies could be further examined.

Pan et al. [89] showed an interesting prospect by developing a fan-shaped cavity (FSC) MC for comparison with traditional rectangular MCHS. FSC showed superior performance compared to conventional design and comparatively small pressure drop penalties. Nevertheless, the degree of coincidence, deviation, and distribution of FSCs have notable effects on HTPs; hence, methods for optimising FSC designs could lead to future research.

Furthermore, Wang et al. [90] examined flow characteristics of bi-directional ribs (BR) MCHS, its mechanism, and underlying heat transfer improvements. For identical mass flow rates, BR MCHS showed significantly better Nusselt number and heat transfer. Additionally, BR-MCHS produced the highest friction factor and blocking effect.

3.3.4. Pin-fin

Research related to pin-fin designs could be significant as per the literature. Nevertheless, Liao et al. [91] appraised flow boiling heat transfer. The conclusions were: mass velocity was directly proportional to the subcooled temperature variations, augmenting the surface HF generated various flow patterns, phase change on boiling induced almost three-times of pressure drop, and raising WF saturation temperature increased pressure drop. Therefore, there are scopes to study the effects of fin inlet alignments and fin arrays on the boiling convection heat transfer.

Additionally, Tiwari et al. [92] investigated the role of precise flow patterns in MCHS via a 3D printed manifold for single-phase flow under low to medium HF conditions. The total HTC for the MCHE reached higher than most available shell and tube heat exchangers. Also, utilising mass-manufactured fin tubes made the overall experimental setup fabrication economically viable. Thus, research is needed for optimised geometry to be used in large-scale heat exchangers. Moreover, the flow pattern in a multitube bundle needs an appraisal for developing shell-ad-tube type MCHE.

Wang et al. [93] investigated single-phase flow heat transfer downstream having one pin-fin. The findings noted vortex shedding and large-scale flow mixing caused higher HTC along the pin fin centreline. The numerical model from this experiment also helped trace the heat transfer map of the heater to the fluid and its surroundings.

Lastly, Zhang et al. [94] recently produced a detailed study on pin-fin-based MCHS optimisation. They investigated the thermal behaviour of a corrugated MCHS with arrayed-fin structures; evaluation was done via performance-based optimisation for fin’s arrangement, angle, lateral and vertical spacing, and the matching of coolants mass flow rate. The results showed a nominal 2% error value between experiments and simulation. Moreover, it was noted that staggered fins performed better but not at higher mass flow rates. Angled fin had an inverse relationship with the pressure drop, and this property was more visible for increased coolant flow rate. Increasing the vertical and lateral spacing of the fins affect the HTP negatively. Consequently, other fin geometries and their manufacturing costs could be assessed.

3.4. Sustainability perspective

The initial literature review indicates a lack of research papers that explicitly focus, cater to, or blend sustainability and MC. Nonetheless, some research could be categorised based on the sustainable aspects noted in their investigations or future scopes. For such cases, deductions and inferences were made to link the studies to different sustainable development elements; these papers are discussed in the following paragraphs. Furthermore, the sustainability aspects were also linked to complement the three MEDS perspectives mentioned in the earlier chapters.

Wang et al. [95] studied HTC and moisture transfer coefficient (MTC) variation in a MC under varying sizes and desiccant thicknesses. The experiments showed that heat and MTC increase with airflow velocity. Also, smaller fin and flat tube pitches exhibited larger heat and MTC. The desiccant thickness negatively affected the HTC but positively impacted the MTC. Furthermore, the Taguchi method analysis concluded that the airflow velocity has a significant impact on the dehumidification process. This paper provided a baseline for future design and manufacture of adsorption chillers, heat pumps, energy storage equipment, and atmospheric water collectors based on DCHE application and effectively promoting sustainable approaches from an environmental sense.

Lin et al. [44] investigated flow boiling in a rectangular vertical MC with heterogeneous wetting surfaces and silicon surfaces. Combining hydrophobic and hydrophilic surfaces manipulated the bubble dynamics and HTP in flow boiling. Moreover, coating a Teflon solution on different positions of the silicon substrate significantly improved the HTP. Future investigation with more heterogeneous wetting surface usage in engineering applications could positively impact cost and ease of manufacture; this, in turn, will have positive impacts on improving profits and economical sustainability.

Li et al. [96] investigated reactant flow rate and pin–fin design effects in MC reactors via time-frequency analysis for two-phase flow pattern transition. The pin–fin outlet reactors suppress the upstream compressible slug fluctuation to produce a conversion of 59.0% for 5 ml/h, the highest value for H2O2 decomposition in MC reactors ever noted. Therefore, there is potential to utilise and mitigate two-phase flow instabilities in MC catalytic reactors and dehydrogenation of liquid organic hydrogen carriers (LOHCs). LOHCs can lead to relatively safer, cheaper storage materials and cleaner energy systems. Thus, MC-based LOHC would further aid both economic and environmental sustainability in the overall production and supply chain.

Lastly, social sustainability is perhaps the most complex sustainability aspect. Nevertheless, the work of Bhattacharjee et al. [97] does indicate the potential of producing socially sustainable developments via MC technologies. Bhattacharjee et al. [97] developed a MC-based strain sensor that showed three times increased resistance value for 10% strain — better than most existing strain sensors. Also, the sensor was responsive to different bending and twisting due to the presence of effective strain. Therefore, the implications of employing feedback control with the strain sensor could help to control a robotic finger movement using human interactions. Consequently, similar future technological advancements will further promote diversity and inclusivity in the industrial workforce, especially for people with disabilities — directly impacting and enhancing social sustainability.

4. Experimental methods and trends

After scanning the available literature, it was found that there was a scarcity of recent papers that provided a detailed assessment of experimental methods and trends in MC. However, authors have sometimes categorised some data/research related to MC shapes or working fluids for their experiments or other purposes. Therefore, it can be said that due to the diverse factors and means available for MC-based experimentation, finding a generalised trend is challenging. Therefore, this research paper will be arguably the first to identify and appraise general trends and elements needed for experimenting with MC. Additionally, the chosen strategy is aligned with the four perspectives in the MEDS framework and the ethos of tackling smaller issues to lead to wider technological advancements. The common, yet critical, elements and data have been extracted from the sample of 70 papers used for qualitative analysis. Table 1 highlights all the data and summarises the findings from earlier chapters for visualisation and analysis purposes; the table has been categorised in reverse chronological order and grouped using the MEDS elements.

As sustainability is one of the paper's themes, to get a general overview of the current trends, the first emphasis was given to the research contribution from each region/continent. Fig. 1 shows the research based on geographical classification; it should be noted that papers, where the first authors were from Turkey, have been put into the Europe region, and Russia has been put into the rest of Asia category. Also, some countries were given their own category.

It can be observed that MC-based experiments are heavily studied in China (37%) and the Rest of Asia (ROA) 29%; they account for 2/3rd of all the research contributions. MC are part of sustainable engineering technologies; therefore, related research carries positive sustainability impacts. In comparison, Europe's (16%) contribution is perhaps slightly underwhelming as MC-based technologies are aligned and undoubtedly provide solutions toward the EU's 2050 climate goals [98]. Also, MC-based research is not frequent in other regions; this can potentially be due to the developing nature of these regions (Africa/South America) or because their (USA/Australia) research areas focus elsewhere.

Fig. 2 shows the FRIN (Further Research Is Needed) trend. It was noted that there had been a relative uptrend in research needs from a design, flow enhancement, and sustainability perspective whilst a relative downtrend from a materials perspective.

Fig. 3 shows the radar plot exhibiting the proportion of FRIN areas; there are more scopes for research from a design perspective (24, 34.3%). Despite materials (22, 31.4%) having a slight edge on flow enhancement (20, 28.6%), considering the overall downtrend for FRIN in the materials area (shown in Fig. 2), perhaps increased flow enhancement research is more suited currently. Similarly, due to the lack of papers linking sustainability (4, 5.7%) and MC, further investigations and frameworks would be beneficial. Since the FRIN areas have relatively similar scores, the authors acknowledge that there may be criticism regarding the chosen methods to prioritise FRIN areas. Nevertheless, the data highlighting the current FRIN status and trend arguably still provide valuable insights for future research directions.

Materials Used (Material/Sustainability Perspective) - Although diverse materials have been used whilst fabricating MC. The most used primary materials for MC were in the form of Polydimethylsiloxane (PDMS), Poly- methyl-methacrylate (PMMA), Copper (CU), Silicon (Si), Aluminium (AL), and Steel. Other materials (OMT) categorise and combines all other materials such as glass, SU-8, tantalum, amongst other unclassified materials not frequently used. Fig. 4 shows the trend of material usage.

Fig. 4 shows that there has been a steady usage of CU MC over time. Polymer-based materials (PDMS/PMMA) and OMT have also seen an uptrend in the past couple of years. Although it can be noticed that there has been a peak utilisation of Si-based MC in 2019, it has since been relatively underutilised. Fig. 5 presents the most common/frequently used materials used for MC. The x-axis shows the materials used, whereas the y-axis represents the percentage/proportions of experiments/papers that utilised those materials for their MC designs. It should be noted that the y-axis information is similar for other figures.

MC Fabrication (Design/Sustainability Perspective) – Fig. 6 shows the trend of MC fabrication over the past five years. MC fabrication processes are reliant on a variety of micromachining (MM), etching (ETC), and lithography (LI), amongst other methods. On average, MM is most consistently used for MC fabrication. Moreover, LI saw an overall uptrend for investigations, but ETC has seen a general decline over the years. Recently, there has been a trend of 3D-printed (3D) MC-based technologies, albeit it has been used sparingly for investigations.

Also, in many experiments, researchers have gone with commercially/premade (CM) MC. Lastly, around 1/4th opted for other distinct other fabrication methods (OFM) or did not provide enough details about their MC fabrication, these two elements combined are shown as OFM in Fig. 7, which shows the data for current levels of MC fabrication

Table 1
Summary of findings.

Author	Shape	DH	AR	PR	MT	WF	Analysis	Country	Contribution
Chiriac et al. [17]	Y-shape	0.05	1	LI	PDMS	W, Oil	CFD	Romania	µPIV result verification
Hoang et al. [18]	Rectangle	0.19	30	OFM	CU	Novec	NM	USA	New correlation model
Liang et al. [40]	Rectangle	*	0.22	CM	OMT	W	UA	China	DHCE MC system
Martinez et al. [27]	Rectangle	0.42	2.83	CM	OMT	ZnO	SIMUL	Chile	Zn nanofluid arrangement
Yin et al. [36]	T-shape	0.4	1	OFM	PMMA	Ethanolamine	NM	China	Chemical absorption
Ahmadi et al. [33]	Square	0.97	30.6	LI	AL	W	NM	Turkey	Biphilic surface high HF cooling
Dalkılıç et al. [20]	Rectangle	0.42	0.81	MM	CU	R134a	UA	Turkey	R134a in two phase flows
Venegas et al. [37]	Rectangle	0.29	20	CM	Steel	WM	NM	Spain	Membrane-based micro-desorber design
Ding et al. [28]	Spiral	0.9	1	CM	OMT	DW, TiO2	NM	China	TiO2-H2O nanofluid
Jayaramu et al. [38]	Rectangle	0.32	2.08	MM	CU	DW	NM	India	Different Wettability surfaces
Roumpea et al. [39]	Rectangle	0.19	1.03	OFM	OMT	HY	MATLAB	UK	MC with surfactants
Yameen et al. [42]	Rectangle	0.65	0.48	3D	Steel	Air-W	NM	USA	3D-printed MC manifold
Abdulbari et al. [22]	Rectangle	0.17	5	LI	PDMS	WM	NM	Malaysia	Drag-reducing agent assessment
		0.16	4						
		0.15	3						
		0.13	2						
Guo et al. [21]	Rectangle	0.08	4.26	LI	PDMS	HY	NM	China	EGaIn usage in MC
Sarafraz and arjomandi [29]	Square	0.4	1	MM	CU	W, Ga	NM	Australia	Application of gallium nano-suspensions
Sarafraz and arjomandi [23]	Rectangle	0.31	0.63	MM	CU	W, CuO2(I)	NM	Australia	CuO/liquid indium nanofluid
Sarafraz et al. [30]	Rectangle	0.31	0.63	MM	CU	DW, Ag	NM	Iran	biological silver-water nanofluid
Simsek et al. [32]	Rectangle	0.08	4	OFM	Glass	HY	NM	Turkey	silver nanowire suspension
		0.07	2						
		0.06	1.4						
zhang et al. [34]	Rectangle	0.69	1.33	3D	CU	DW	NM	China	3D heterogeneous wetting MC surfaces
zhang et al. [41]	Rectangle	0.3	1.56	3D	Inconel	N2	NM	USA	3D-printed Inconel 718 MC manifold
Bae et al. [43]	Rectangle	0.02	0.2	ETC	SiC	R245fa	NM	USA	Embedded cooling system
Sarafaraz et al. [31]	Rectangle	0.31	0.63	MM	PDMS	HY	NM	Iran	carbon nanotube nanofluid
Lei et al. [55]	T-shape	0.4	1	MM	PMMA	Glycerol, Si	MATLAB	China	Prediction scaling laws
Lin et al. [51]	Rectangle	0.2	1	OFM	OMT	W, Si	CFD	China	Novel CFD solver
Matin and Moghaddam [54]	Rectangle	0.12	4	OFM	PDMS	OWF	NM	USA	Critical shear stress at liquid-vapour interface
	Rectangle	0.2	2						
	Square	0.3	1						
Oudebrouckx et al. [52]	Rectangle	0.02	4	OFM	CU, AU	WM	NM	Belgium	Transient Thermal Offset method
Zhang et al. [94]	Rectangle	1	5	OFM	AL	W	CFD	China	Corrugated MCHS
Al Siyabi et al. [66]	Rectangle	0.67	0.5	OFM	AL	W	NM	UK	MLM heat sinks
Garg and Agrawal [61]	Rectangle	0.13	0.49	LI	PDMS	N2	NM	India	High Knudsden number experiments
Garg and Agrawal [63]	Rectangle	0.13	0.49	LI	PDMS	N2	NM	India	Mach/*Re* number relationship
Ji et al. [65]	Rectangle	0.4	2	OFM	PMMA	W, Oil	NM	France	High flowrate emulsification
		0.6	1						
Panda et al. [48]	Circular	0.86	1	OFM	OMT	OWF	CFD	Japan	Two-phase refrigerant maldistribution
Wang et al. [47]	Rectangle	0.3	0.41	ETC	OMT	R134a	NM	China	New empirical method
Al-Siyabi et al. [67]	Rectangle	0.67	0.5	MM	AL	W	CFD	UK	MLM arrangements
Qian et al. [57]	Square	0.6	1	OFM	GLASS	WM	CFD	China	Dynamic dispersed phase injection
Ronshin and Chinnov [56]	Rectangle	0.1	200	OFM	Steel	DW	NM	Russia	Method to determine regime boundaries
Xia et al. [49]	Rectangle	0.1	1.88	ETC	Si	W	NM	China	Triangular corrugated MC
		0.12	1						
Kovalev et al. [59]	T-shape	0.12	1	CM	SU8	WM	SIMUL	Russia	New hydrodynamic features of plug flows
		0.16	0.5						
Kravtsova et al. [60]	T-shape	0.12	1	CM	SU8	WM	SIMUL	Russia	Flow regime distribution features
		0.16	0.5						
Wang et al. [64]	Rectangle	0.12	7.14	OFM	PDMS	DW	CFD	USA	Surface acoustic wave pumping
Zhai et al. [68]	Rectangle	0.11	3.57	MM	Si	DW	NM	China	Flow prediction theoretical model
Zhang et al. [58]	Rectangle	0.13	2	ETC	Si	WM	NM	China	Two phase flow condensation
Abdo et al. [76]	Rectangle	0.15	3	3D	OMT	W	UA	Egypt	Hybrid CPV-TEG-MCHS
Haghighinia et al. [85]	Circular	0.8	1	LI	PDMS	W, Rhodamine	CFD	Iran	Split and recombine mixing
		0.16	1						
Özdemir et al. [57]	Rectangle	0.56	2	CM	CU	DW	NM	Turkey	Small AR comparison
		0.56	0.39						
Ringkai et al. [77]	T-shape	0.57	0.2	OFM	PMMA	Oil, Polysterene	MATLAB	Malaysia	Time-resolved image sequencing
		0.4	1						
		0.5	1						
		0.75	1						
Vinoth and Sachuthananthan [78]	Rectangle	1	1	MM	CU	AL2O3/CUO	NM	India	AL/CU based nanofluids
Hou and Chen [79]	Square	*	*	MM	Steel	W	CFD	China	*Re*-entrant cavity shapes
Luo et al. [71]	Rectangle	1	1	OFM	OMT	W	CFD	China	Annular flow boiling hydrodynamics
Oudah et al. [86]	Rectangle	0.83	0.2	MM	CU	W	NM	USA	Optimum IR dimensions
Ye et al. [80]	Rectangle	0.71	13.12	LI	PDMS	DW, N2	CFD	China	Microchannel with gas cavities
Kumar [87]	Triangular	0.46	3.33	OFM	Si	DW	CFD	India	Trapezoidal MC with grooves
	Rectangle	0.35	0.32						
Li et al. [72]	Rectangle	0.2	1	MM	Si	DW	NM	China	MC with hydrophobic surfaces
Liao et al. [91]	Circular	0.51	1.04	MM	TA	FC-72	NM	Taiwan	Inlet alignments
Ma et al. [88]	Rectangle	0.05	1	ETC	Si	Acetone	NM	China	Zigzag MC flow boiling
Nadaraja et al. [81]	Rectangle	0.15	10	MM	CU	W	NM	Malaysia	MLM arrangements

(*continued on next page*)

Table 1 (*continued*)

Author	Shape	DH	AR	PR	MT	WF	Analysis	Country	Contribution
Pan et al. [89]	Circular	0.89	0.8	OFM	CU	DW	NM	China	FSC design
Tiwari et al. [92]	Elliptical	1	1	3D	CU	W	UA	USA	Novel 3D-printed MCHE
Wang et al. [90]	Rectangle	0.5	0.7	MM	Si	DW	CFD	China	MC with bi-directional ribs
Jia et al. [50]	Rectangle	0.47	0.9	ETC	Si	OWF	NM	China	Porous wall MCHS
Wang et al. [93]	Rectangle	0.35	7.5	ETC	Si	Novec	CFD	USA	Single-phase flow
Duryodhan et al. [74]	Spiral	0.09	3.33	Li	PDMS	W	CFD	India	Spiral MC mixing
		0.13	2						
		0.2	1						
Li et al. [82]	Rectangle	0.38	20.5	ETC	Si	Acetone	OAM	China	MC with triangular cavities
Vinoth and Senthil [83]	Square	0.85	1.13	MM	CU	HY	UA	India	Oblique-finned MCHS
	Circular	0.85	1.13						
	Trapezoid	0.85	1.13						
Walunj and Satyabhama [84]	Square	0.5	1	ETC	SI	DW	NM	India	Open microchannels
	Parabolic	0.57	1.3						
	Parabolic	0.43	0.75						
	Stepped	0.57	1.3						
	Stepped	0.43	0.75						
Yin et al. [75]	Rectangle	0.57	20	CM	CU	DW	NM	China	Large AR
Li et al. [96]	Rectangle	0.38	0.04	ETC	SI	H2O2	MATLAB	China	H2O2 decomposition method
Lin et al. [44]	Rectangle	0.91	10	OFM	SI	DW	NM	China	Heterogenous wetting surface
Wang et al. [95]	Triangular	*	*	CM	OMT	W	NM	China	DCHE-based dehumidification
Bhattacharjee et al. [97]	Circular	0.18	1	OFM	PDMS	Polymer	NM	UK	Strain sensor feedback control

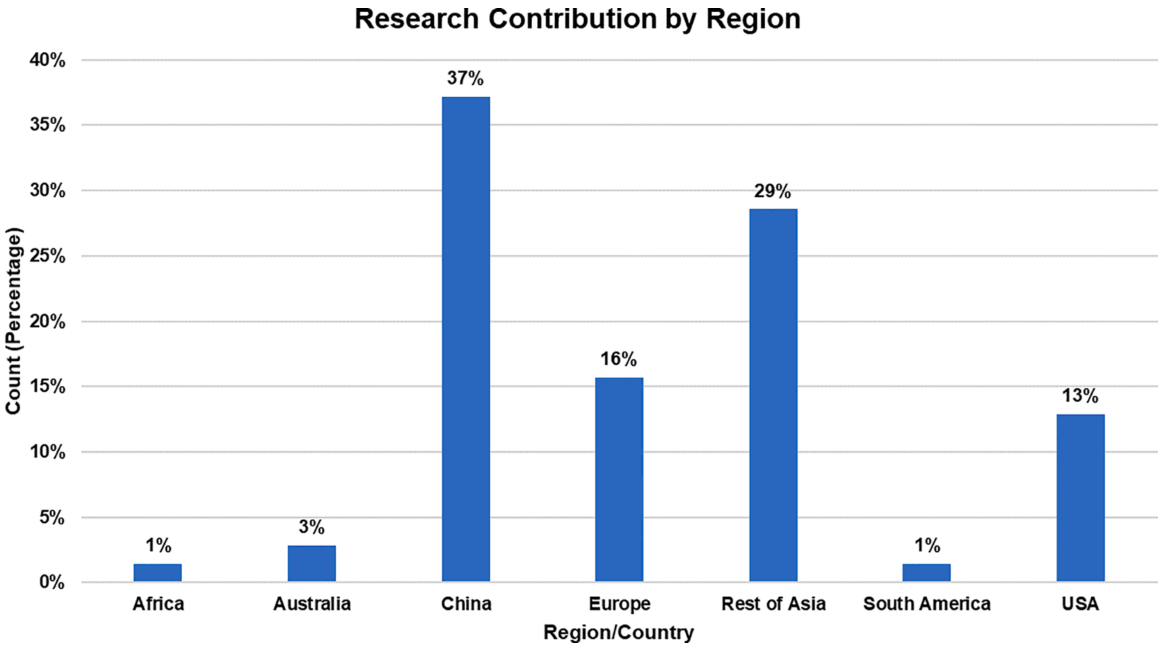

Fig. 1. Research contribution by region.

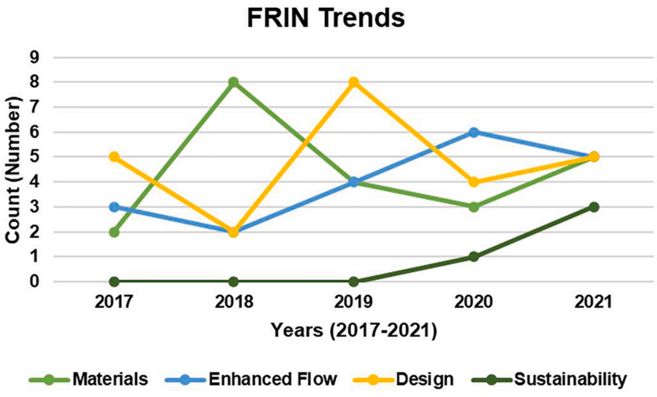

Fig. 2. FRIN trend.

methods.

Working Fluids (Material/Sustainability Perspective) – Fig. 8 shows the trend of most used working fluid for MC experiments. Water (W) and water-mixture solutions (WM) have generally been used more frequently in recent years, but de-ionised water (DW) has seen a decline. Similarly, hybrid nanofluids/microfluids (HY) consisting of elements such as aluminium, copper, silver, amongst others, are also getting used in recent years. Also, other working fluids (OWF) such as Novec, R134a, FC-72 have seen a general uptrend in usage. Nitrogen (N2) gas utilisation is also a notable observation as a WF; however, their utilisation has been irregular and used for distinct investigations. Fig. 9 summarises the MC working fluid trends and current usage.

MC Design/Configuration (Design Perspective) - Fig. 10 shows the design trend for MC shapes/configurations. Some researchers experimented with more than one shape/design for their investigations; as a result, the total data points for MC configurations/shapes stand at 80 instead of 70. Assessing the papers from the last five years, the trend of

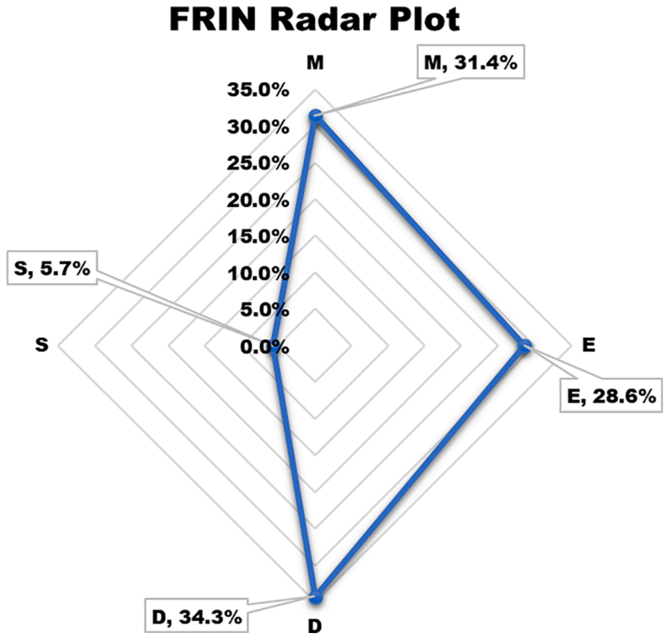

Fig. 3. Future research scopes.

using traditional rectangular MC configuration is still valid.

However, square or circular shapes are also utilised, along with a T-shape junction. Other case-specific structures such as spiral or y-shape MC also exist. Nevertheless, novel-shaped designs are not frequently experimented with, and the current MC designs are still primarily dominant on a rectangular-shaped geometry as shown in Fig. 11.

Analysis Methods (Enhance Flow Control Perspective) – Fig. 12 shows the analysis methods employed by researchers for MC-based studies. The focus of this paper is on heat transfer and thermal management application; therefore, in almost all experiments, general flow visualisation analyses exist. However, most papers rely on basic numerical methods (NM) for analysis and solving flow equations.

Computational Fluid Dynamics (CFD) is the second most used analysis method. There has also been some emphasis on uncertainty analysis (UA) and simulations based on MATLAB. Other analysis methods via machine learning techniques have also been noted, but they were not as frequent as numerical methods and flow visualisation; this can be seen in Fig. 13. Nonetheless, numerical methods are still the dominant (pie-

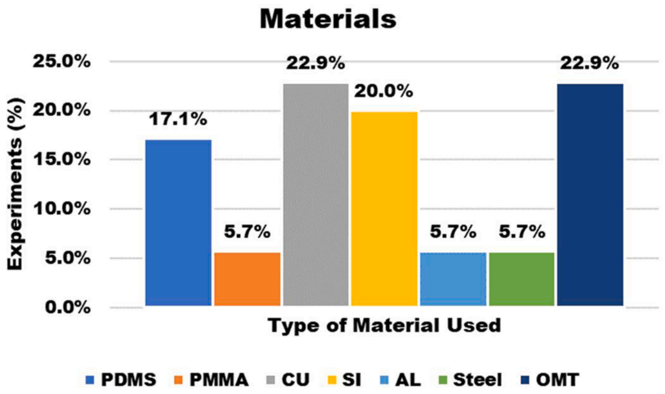

Fig. 5. Materials usage.

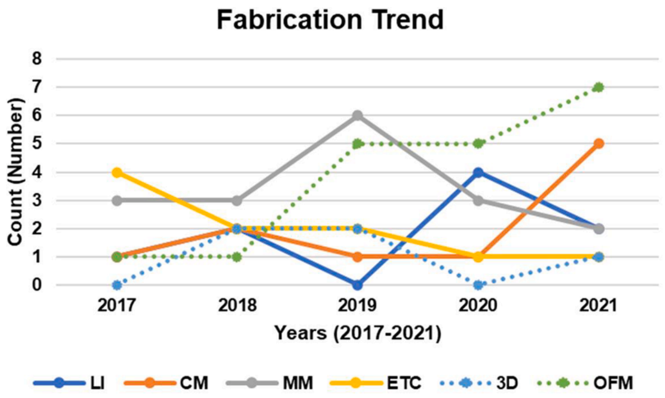

Fig. 6. Fabrication trend.

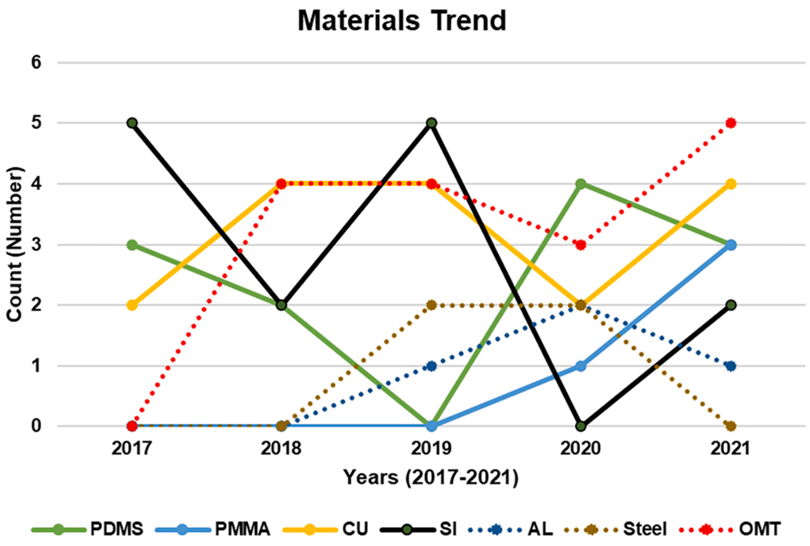

Fig. 4. Materials trend.

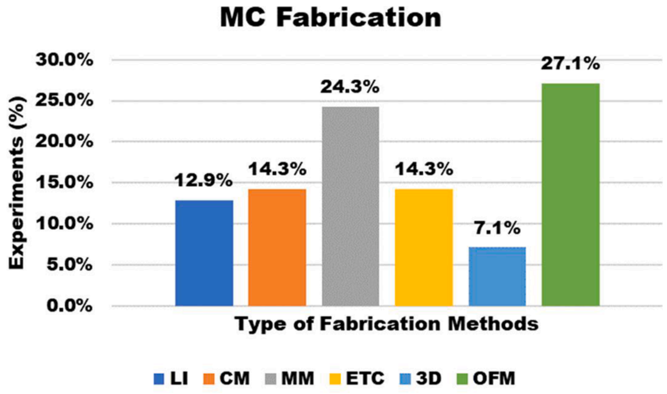

Fig. 7. MC fabrication methods.

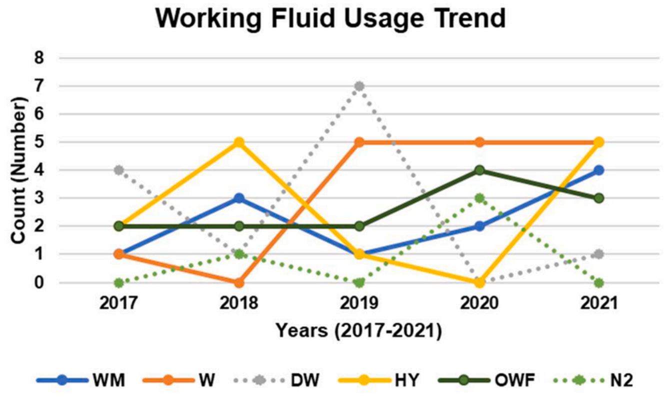

Fig. 8. Working fluid trend.

chart use for easier visualisation) analysis methods for MC studies.

Hydraulic Diameter (Design Perspective) - the hydraulic diameters (DH) of MC, calculated using the width and height of a design, lie between 0.01 to 1. Therefore, the data was segmented into 0.1 intervals to assess the trend of the most utilised DH for experiments. Fig. 14 shows a Pareto Chart to provide better overall visualisation of the data trend for diameters. It can be seen almost 40% of the experiments used a DH between 0.01–0.2 range (note: some papers used multiple designs/configurations for their experiments; thus, the data count for DH and AR is more than 70).

Aspect Ratios (Design Perspective) - Aspect Ratio (AR) is also given by the width and height of MC; therefore, they were also visualised along with the DH. However, due to the wide range of AR observations, the data were qualitatively categorised, based on their value ranging from small to extra-large — as shown in Fig. 15. 90% of the experiments were conducted using an $AR<10$.

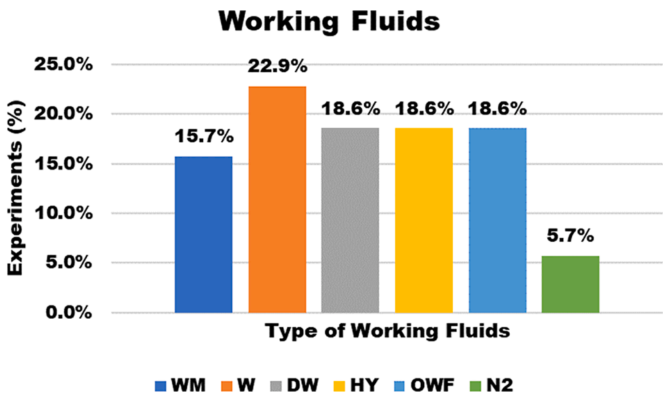

Fig. 9. Working fluid usage.

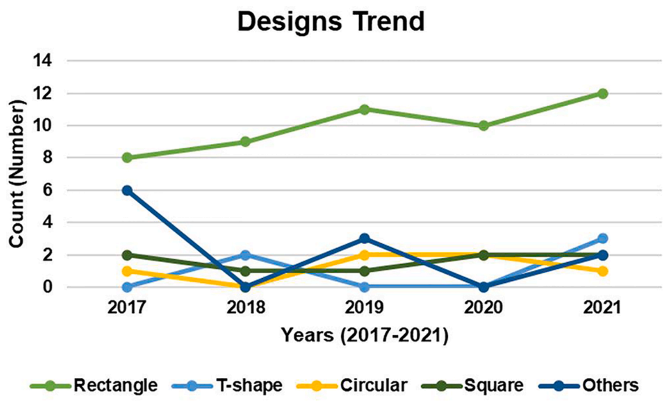

Fig. 10. Design trend.

5. Critical discussion

5.1. Research and experimental trend

In terms of MCHS designs/shapes, combining the traditional rectangular (62.5%) and square (10%) shaped channels account for around 3/4th of all MC structures; other distinct non-traditional designs/shapes account for 13.8%. Therefore, investigations on different MC structures with non-conventional geometry are a promising area as per findings from the extant literature. The positive implications of utilising multi-layer/3D MC have been presented during the qualitative analysis;

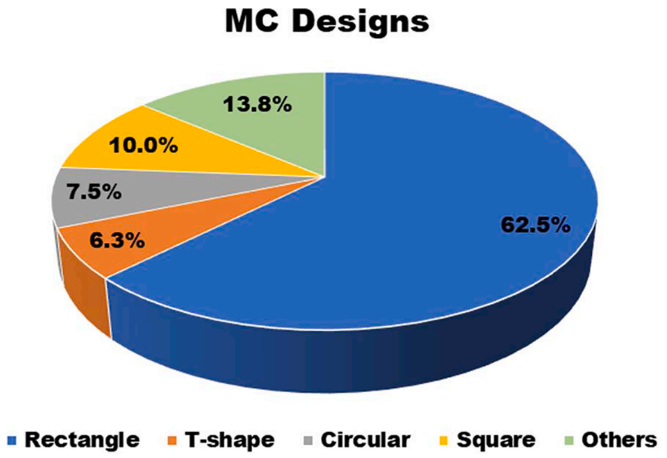

Fig. 11. Different design implementation.

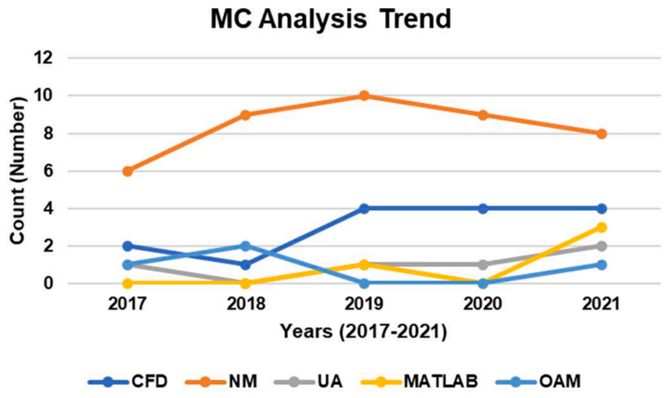

Fig. 12. Analysis trend.

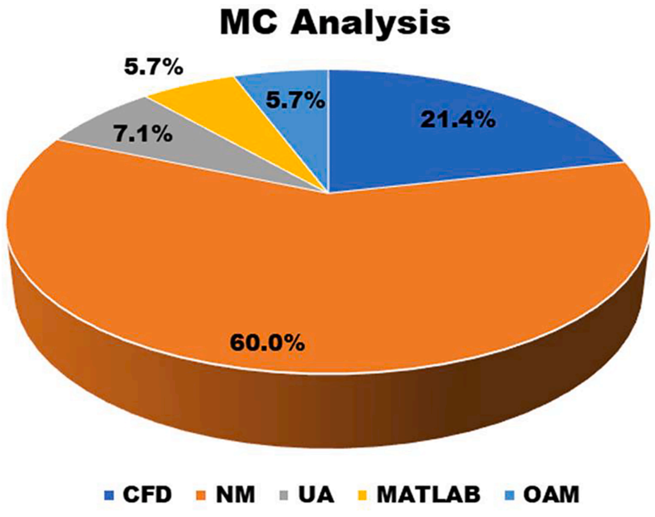

Fig. 13. Analysis methods.

however, there is also potential to improve future MC via other means. The recent adoption of generative designing, generative- adversarial networks (GANs), additive manufacturing, and high precision micro-machining technologies make novel methods such as bio-inspired structures [99] and fractal designs [100] viable options to employ for upcoming MC technologies.

On the other hand, material usage in MC shows a more distributed trend. PDMS (17.1%), CU (22.9%), and Si (20%) tend to be the most common materials. Considering the other two metal usage AL (5.7%) and Steel (5.7%), the three most-used metals combine to around 34.3% or 1/3rd of all MCHS. Alternatively, considering polymers such as PMMA (5.7%), polymers total around 22.8% or 1/4th of all materials approximately. The type of material used for mass production of MC will need to consider various internal and external factors such as HTP, ease of manufacture, cost trends, and sourcing challenges, amongst others. Consequently, this would provide another valuable research area. The trends for MC fabrication display a mixture of methods. Whilst many authors have detailed their strategies, others have not divulged sufficient information regarding their MC fabrication (OFM, 27.1%) for their experimentation. Nevertheless, the data show the utilisation of some form of micro-machining (24.3%) — the most frequently used method. Next, lithography (12.9%) and etching (14.3%) are mostly used, but the utilisation of additively manufactured (AM) (7.1%) MCs are less frequent. Cost is potentially the primary reason to dictate fabrication choices. Commercially made MC (14.3%) have also been noted; however, these types of MC generally focus on ’fit-for-purpose’ experiments or analysis rather than the design aspects. Therefore, there may be debates attached to these experiments regarding their generalisability or innovativeness.

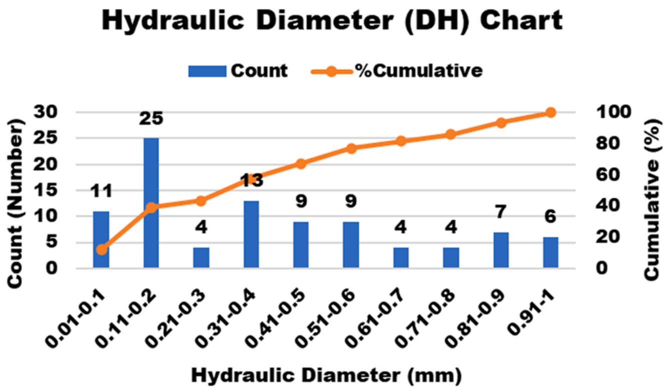

Fig. 14. Hydraulic diameter trend.

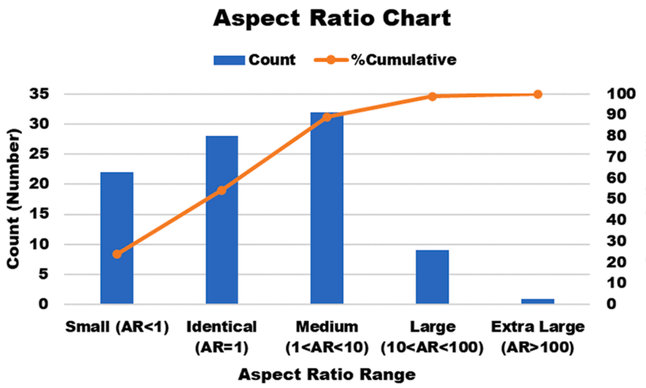

Fig. 15. Aspect ratio trend.

Despite the literature indicating that 3D-manufactured MC-based structures provide positive implications, the under-utilisation of AM can perhaps be due to the difficulty of producing extremely accurate micro-scale products with high tolerance levels or because they are economically unfeasible. Compared to other methods, additive manufacturing (AM) is sometimes considered more sustainable and can produce complex shapes. Also, AM can employ materials such as polymers, metals, alloys, and ceramic materials for production, which is advantageous but also gives rise to standardisation of materials issues [101]. Moreover, AM has issues producing uniform surface finishes, and post- processing is often required to reach uniform surfaces or shapes. On a different take, the non-uniform surface finish can perhaps be turned into an advantage since previous studies showed that surface roughness/cavities enhance HTC with lower pressure drops [38]. Nonetheless, the feasibility of AM for microscale dimensions and mass-producing microchannel setups needs further appraisal and innovation to make it more viable for adoption.

Currently, it can be remarked that AM technology is not yet suitable for some use cases. Consequently, this indicates a research area to exploit. Moreover, numerous researchers insisted that manufacturing processes cause the most significant energy consumption and sustainable impacts on a product’s life cycle. Thus, studies to focus on identifying sustainable MC manufacturing practices and their impacts can also improve the overall sustainability within this industry.

The working fluids used in MC-based experiments tend to be mainly water-based, generally safe and sustainable. Nevertheless, the effectiveness of new refrigerant-based or mixed metal-based nanofluids needs further assessment in not only performance but also usage and disposal. The quantitative data from Fig. 15 shows agreement with the qualitative findings that large AR needs to be explored. Therefore, the argument made by [75] can be backed with data to trigger investigations into large MC ARs; albeit, the pressure drop consideration and DH of the new designs need to be manipulated and experimented with for optimised performance. Moreover, ML/AI techniques can also aid this process in quickly predicting flow and visualising for several AR/DH combinations and giving flow predictions. Also, incorporating MC systems into cloud computing or Digital Twins systems would provide continuous improvement and innovation throughout the product development and testing.

Overall, the recent general trends in microchannels research still show many dependencies on traditional methods. It is noted that technological adoption within MC development is gradually evolving. However, there are many issues within this sector relating to the speed of technological adoption, standardisation, scalability, fabrication, and sustainability — to some extent. It can be debated that technologies such as additive manufacturing, machine learning, cloud computing, and digital twins have already been deployed for MC-based technology. Despite that, in-depth investigations and even reassessment of previous experiments are needed to influence further performance and design innovations. The authors were mindful that other minor trends or themes could have been appraised in this paper. However, due to the complexity and data availability, the authors selected themes, trends, and experimental methods that were better aligned with the past research, research questions, and reflect current literature levels.

5.2. Key research themes and sub-themes

The key research themes (MEDS) and their sub-themes were determined and were categorised as follows: Materials (working fluids, nanofluids/nanoparticles, and surface treatment/manipulation); Experimental (flow boiling, phase change, flow resistance, thermal resistance, and manufacturing techniques); Design (aspect ratios, geometry/shape manipulation, barriers, and pin-fins); Sustainability perspective (no general theme, environmental, economic, and social).

Firstly, focusing on the material:

1 As per the findings from the literature, utilising hydrophobic refrigerants as a working fluid deliver a positive impact on the two-phase flow HTC and extends nucleate flow boiling length, provided the inlet temperature and HFs are progressively increased, respectively. Additionally, utilising two working fluids has generally shown to be reliable compounds during monitoring and verification heat transfer- based experimentation. However, relatively higher temperatures are required for working fluids to be effective and there is scope for further research due to uncertainty on the effect of hydrophilic/hydrophobicity of working fluids on heat transfer, pressure drop penalties, and especially for non-Newtonian fluid experiments;

2 Metal-based nanofluids mixture, especially one containing silver, can significantly improve HTC; nanofluids have also been shown to improve the thermal conductivity of the base fluids. Though, increased pressure drops and friction factors are the leading drawbacks of nanofluids usage. There is also a lack of consensus regarding how nanofluids affect thermal resistance and two-phase flows. Previous studies have indicated long-term stability issues and increased pumping power requirements in nanofluids usage [102]. However, the study of Simsek et al. [32] indicates that nanofluids can increase HTC without added pumping power. Therefore, the viability of silver nanofluids for reduced pressure drop, friction factors, and two-phase flow needs further research;

3 The literature suggested that the trend for common surface treatments was employing different wettability surfaces, surfactant additions, chemical treatment, and desorption. However, high thermal conductivity materials, such as diamond, for surface hydrophilization present alternate options to provide heat transfer enhancement [103]; albeit, they may not be the most cost-effective solutions. The coating surface appears to produce a significant impact. To illustrate, surface wettability variations in flow boiling investigations improved HTC, and biphilic surfaces (BS) and 3D heterogeneous surfaces provide enhanced flow boiling heat transfer and improved nucleation density. These heat transfer enhancements primarily occurred because the thermal boundary layers during two-phase heat transfer rely on factors such as cavity size, surface roughness, surface wettability, and surface morphology [34]. For instance, gases trapped in the pores and cavities can trigger bubble nucleation [104], whilst a hydrophobic surface enjoys a lower interfacial energy barrier compared to its hydrophilic counterpart [105]. Nevertheless, there is a lack of clarity on how surface manipulations affect pressure drops and thermal resistance.

4 Overall, the studies of Ahmadi et al. [33] and Jayarmu et al. [38] indicated that whilst surface wettability has been studied in pool boiling, there is a lack of research on the effect of surface wettability in flow boiling. Consequently, this gives rise to future research areas. Elevated surface wettability tends to give higher HTC, but with higher pressure drops and reduced CHF values. On the other hand, low surface wettability produces comparatively higher CHF values and reduced pressure drops. Furthermore, care must be taken whilst increasing surface wettability as it can lead to the thermal oxidation of materials. A biphilic surface or mixed wettability surface for flow boiling-based applications is perhaps one of the most promising areas to explore as they can utilise both types of wettability surfaces to yield the desired results. Therefore, subsequent research can focus on employing different biphilic surfaces for flow boiling pressure drop and thermal boundary layer formation assessment

Secondly, considering the experimental elements:

1 Researchers have emphasised flow boiling instability and friction resistance. However, it should be noted that there are some disagreements and lack of clarity on how flow boiling enhancement can be achieved due to the complex mechanism and number of factors related to flow boiling and two-phase flows [46]. Nonetheless, research has shown that frictional pressure drop penalties could be reduced via increasing inlet saturation temperature and adding inlet restrictors;

2 Phase change phenomena via slug generation and control lead to improved heat transfer, but critical shear stress and interfacial tension need considerations to gain optimal results;

3 The thermal resistance of MLM heat sinks can be reduced by using a multi-layered MCHS, but thermo-electrical performance needs further appraisal;

4 Convective thermal resistance and the length of entry channels represent critical factors for enhanced heat transfer. If mixing and turbulent flows are warranted, asymmetrical flow regimes/setups improve general performance;

5 Additive manufactured MCHS are also becoming viable candidates and can produce pin-fin with a thickness of 0.18 mm. Additively manufactured MCHS have shown improved HTP, but further assessment is required for its feasibility for other dimensions.

Thirdly, appraising the design parameters:

1 Appraising the papers, there was no general trend regarding the effect of AR on heat transfer, flow boiling, and pressure drops. Though, it was noted that in specific cases, AR could impact the flow mixing, boiling heat transfer, instability, and pressure drops; this is more noticeable at low heat flux conditions. Though, there was a lack of clarity regarding how AR (high or low) affect the flow boiling due to the complex mechanism. The findings of this research align with previous studies that claimed that the results of AR effects were contradictory, and developing a general conclusion regarding AR effects on flow boiling/two-phase flow is challenging [106,107]. However, depending on the heat flux and mass flux, it can be said that using high AR provide larger nucleate boiling regions, comparatively lesser flow instability, and higher HTC but also cause higher pressure drops. Also, HTC at higher HF is unaffected by small AR; alternatively, HF under 480 kW/m^2 and mass flux can adversely affect the HTC. For high AR, increasing wall HF reduces the thickness of the liquid film and, in turn, improves the local HTC considerably; nevertheless, researchers need to be mindful of the wall HTC if inlet HF is increased; Large AR have also shown prevalent nucleate boiling region along with improved HTC for churn flow, but these require further assessment for verification.

2 Improved heat transfer performance and mixing via geometry manipulations can be gained by adding triangular/zigzag cavities at sidewalls, circular/semi-circular re-entry shapes with barriers, and trapezoidal/pentagonal designs. However, the flow velocity within the microchannels needs to be monitored as increased flow leads to higher pressure drops;

3 Barriers can provide improved flow boiling stability depending on the configuration and operating conditions. At low HF, multiple-barrier setup delivers better performance; on the other hand, at high HF, fewer/single-barrier had better results. Similarly, grooves, wavy, or zigzag configurations appear to suit more in high heat flux conditions to provide better stability. However, barriers can also disrupt the flow, provide a high friction factor, and flow mixing; thus, care must be taken whilst implementing barriers to ensure desired effects. As a result, more studies are required to establish the previous conclusions.
4 Overall, adding barriers and flow restrictions, in general, have shown positive performance improvements in microchannels. For single-phase flows, the addition of pin-fins provided higher flow mixing and HTC. The general theme also shows that pin-fins are typically employed to increase the surface area for heat transfer enhancement, but barriers or restrictors show more diverse utilisation. As previous studies indicated, it is arguably complex to claim the best setup for either barrier or pin-fin configurations as flow boiling instability and pressure depend on several factors and further research is needed regarding many dependencies. The same pin-fin may generate vastly different results if different surface roughness, heat flux, mass flux, aspect ratios, and nanofluids are used. However, the findings from this research and recent studies have shown that pin-fin setups can improve flow boiling with reduced pressure drops and instability compared to conventional geometries [108,109].

Lastly, for sustainability, numerous authors suggested that adopting modern technologies to provide better energy-efficient methods will lead to sustainable development and improve overall sustainability. Therefore, it can be debated that all MC-based research indirectly contributes towards sustainable development within industries. However, sustainability remains a complex concept, possessing multiple factors; therefore, finding general research themes is challenging. Nevertheless, different experiments could perhaps be categorised into economic, environmental, and socially sustainable elements. Consequently, presenting diverse research areas to conduct more focused investigations can lead to better long-term sustainable solutions — rather than treating sustainability as an after-effect of MC-based studies.

6. Conclusions

In conclusion, this paper aims to perform a systematic appraisal and investigation of the different microchannel (MC) based research, trends, and experimental methods, focusing on heat transfer and thermal management applications. RQ1 identified and discussed key research themes and sub-themes from recent literature. The qualitative discussion was segmented into four perspectives via a novel material, enhanced flow control, design, and sustainability (MEDS) framework. The utilisation of mixed metal nanofluids, inducing flow boiling instability via barriers, and pin- fins all have beneficial impacts on heat transfer performance (HTP); however, pressure drops need to be a key consideration for all processes. RQ2 appraised gaps in the extant literature and future scopes (FRIN). The qualitative data revealed that most researchers call for research needs from a design and experimental point of view. Moreover, there is also a need to link current research with sustainability rather than regarding it as an indirect impact of MC technologies. RQ3 evaluated experimental trends observed from recent literature via quantifying and classifying the qualitative data. It was identified that the most frequently used methods relating to MC are traditional rectangular shapes for designs/structure, copper as material, water-based working fluids, micromachining for fabrication, and numerical methods/flow visualisation for analysis. In the Industry 4.0 era, it is arguably essential to embrace novel technologies and continuous innovation to stay technologically relevant and provide more sustainable heat transfer solutions.

Although, as previous studies indicated, it is challenging to formulate a general conclusion regarding the best options for microchannel-based heat transfer and flow boiling, we have attempted to deliver a holistic view and recommendations. Therefore, based on the findings from this review, the authors recommend the following:

1 Deionised water as a working fluid — it is a frequent choice for experiments and is sustainable; refrigerant as working fluids also indicated significant flow boiling enhancement, but there are possible environmental impacts;
2 Pin-fin-based geometry, pentagonal/trapezoidal shapes, wall cavities, or zigzag setups are advised over traditional rectangular configurations;
3 Adding roughness and biphilic/mixed wettability surface, compared to wholly hydrophobic/hydrophilic surfaces, may lead to better heat transfer performance and pressure drops in two-phase flow boiling, but this needs further assessment;
4 For operating conditions, manipulating with increased inlet saturation temperature along with the wall temperature is also recommended;
5 The utilisation of hybrid materials, especially silver, or materials with high thermal conductivity can be the choice of materials for both manufacturing and nanoparticles, but cost aspects of material and stability of nanofluids remain a challenge;
6 Lastly, micromachining methods are generally reliable options, the viability of other innovative technologies or additive manufacturing remains an area that needs assessment for more sustainably fabricated microchannel designs.

Acknowledging the research limitations and criticism that may arise from this study, the data and findings are still of quality. It can be validated through the followed research ethical and quality considerations and data collected from the high-quality extant literature. Lastly, the highlighted research gaps can trigger future investigations, provide data for current market trends in MC, aid researchers, academics, and senior management to make quicker, informed, and sustainable decisions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cep.2022.109155.

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