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Review article

Vortex generators in heat sinks: Design, optimisation, applications and future trends

Mohammad Ismail [a,*], Abdullah Masoud Ali [b], Sol-Carolina Costa Pereira [c]

[a] *Department of Renewable Energy Engineering, Amman Arab University, Amman, Jordan*
[b] *Faculty of Engineering, Sabrataha University, Sabrataha, Libya*
[c] *School of Computing, Engineering & the Built Environment, Edinburgh Napier University, EH10 5DT, UK*

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ABSTRACT

Vortex generators (VGs) have been identified as an exceedingly effective method in augmenting heat transfer in minichannels, a significant feature of cutting-edge heat sinks, heat exchangers and electronics cooling tools. This paper aims to discuss the various types of vortex generators, specifically delta winglet, rectangular winglet, trapezoidal and perforated, as well as their impact on improving convective heat transfer. This study focuses on the configurations that define geometric parameters, including the angle of attack, height and spacing in relation to the improvement in thermal or hydraulic performance. Strategies such as nanofluids, dimples, Response Surface Methodology analysis and Artificial Neural Networks are crucial to improve VG designs to maximise thermal efficiency and minimise pressure loss. Additionally, the paper considers potential trends, such as the further miniaturisation of the VGs in terms of micro-level utilisation, more intricate VG shapes, together with the development of smart VGs that can alter their configuration depending on the current thermal conditions. To conclude, this review will provide beneficial information pertaining to current VG technology, the application of VG in high-performance cooling systems, and also identify areas for future research concerning VG technology.

1. Introduction

The increasing demand to meet thermal management requirements have prompted substantial interest in developing miniaturised, efficient thermal management structures, notably within the microelectronics, energy storage, aerospace and automobile industries. Owing to the continued miniaturisation and densification of systems, it is becoming even more crucial to effectively manage the heat these particular systems generate. This is in accordance with the fact that high temperatures can reduce the reliability and efficiency of electronic components or an entire system. Hence, this has brought about an urgent demand for the development of novel, more efficient cooling technologies, principally microchannels and minichannels, where the high surface area to volume ratios promote effective cooling within limited areas [1–3].

Amongst the various types of minichannel heat sinks, there has been increased concern in those that are capable of accommodating high heat flux densities in a comparatively small size. In relation to electronics cooling, heat exchangers and other thermal management applications have also been demonstrated to boost system efficiency. Nonetheless, a significant concern associated with minichannel heat sinks is the development of the thermal boundary layers adjacent to the channel walls and top surface. If the boundary layers are not sufficiently disrupted, the performance of the cooling system can be negatively impacted predominantly in other high-performance cooling applications [4–6].

Amongst the potential solutions, vortex generators (VGs) are notable as a particularly promising approach. VGs are flow structures installed on the walls of a channel creating vortices in the flow that increase turbulence and improve the mixing of a fluid. These vortices disrupt the thermal boundary layer and therefore, increase the heat transfer convection rates. Consequently, VGs disrupt the boundary layer, resulting in a reduction in the resistance in the thermal layer and an increase in the heat transfer coefficient. This method is extremely effective in boosting the performance of minichannel systems with minimal modification in the design [7–9].

Several types of VGs are available in a variety of types and sizes, with each possessing distinct benefits that are appropriate for different applications. Common designs employed in this sort of winglet vortex flow, include the delta winglet vortex generator, rectangular winglet vortex generator and trapezoidal vortex generator. Thus, each of these shapes generates individual flow patterns that generate different outcomes

* Corresponding author.
E-mail address: m.ismail@aau.edu.jo (M. Ismail).

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Nomenclature

VGs	Vortex generator
LVGs	Longitudinal vortex generators
HE	Heat exchangers
DWP	Delta winglet pair
COP	Coefficient of performance
RWVGs	Rectangular winglet VGs
MCHS	Microchannel heat sink
ANN	Artificial neural network
TWL	Trapezoidal wing longitudinal
KVG	Karman-VG
CRVP	Counter-rotating vortex pair
FRs	Flow redistributors
TVG	Transverse VG
PCRWs	Perforated concave rectangular winglets
PCRWP	Perforated concave rectangular winglet pair
BR	Relative heights
PR	Longitudinal pitch ratios
PTVG	Perforated trapezoidal
LP	Longitudinal pitches
LF-CFU	Louvered fin-common flow up
CTVG	Curved trapezoidal vortex generators
DWU	Delta-winglet-upstream
RSM	Response Surface Methodology
CVGs	Cylindrical VGs
D	Diameter
COP	Coefficient of performance
ΔP	Pressure drop
Nu	Nusselt number
f	Friction factor
HTE	Heat transfer enhancement
Re	Reynolds number
CFD	Computational fluid dynamics

because of the heat transfer and pressure drop (ΔP). In recent years, perforated vortex generators have attracted attention for their ability to achieve low pressure loss and high heat transfer whilst delivering a useful balance between thermal efficiency and hydraulic performance [10,11].

In comparison to segmented flow reactors, VGs are acknowledged to significantly increase the Nusselt number (Nu), although they also increase the friction factor (f), giving rise to a high ΔP. Balancing this trade-off between heat transfer enhancement (HTE) and further flow resistance is, therefore, fundamental to the design of efficient systems. Incorporating VGs into minichannel heat sinks can produce boost heat transfer by up to 70 % in particular arrangements. However, the ΔP penalty might impose constraints in specific cases, primarily where low pumping power is considered necessary [12,13].

More recently, interest has intensified in evaluating VGs with nanofluids. These are fluids with additional nanoparticles that have a higher thermal conductivity than the base fluid. The incorporation of nanofluids in conjunction with VGs present an excellent solution owing to a combination of the nanofluid's thermal properties and the increased heat transfer rates attributable to the formation of vortices. This approach is exceedingly advantageous in applications where thermal dissipation and the miniaturisation of the cooling system is essential, for instance in high-power electronics [14,15].

Moreover, optimisation methods, e.g., Response Surface Methodology (RSM) and Artificial Neural Networks (ANNs) have notably advanced VG designs by attaining a high level of accuracy between heat transfer enhancement and ΔP. These methods allow researchers carefully examine the effects of geometric parameters relative to the angle of attack, VG height and spacing, etc. Accordingly, the above parameters can be maximised while reducing the energy required to circulate the fluid through the system, updating the application of VGs for existing thermal control issues [16–19].

In relation to VG research, several promising trends can be identified with regards to future developments. One possible development entails reducing the size of the VG allowing it to be employed in micro-power systems including microelectromechanical systems and microfluidics. Consequently, on the micro scale, cooling solutions will remain important as the components continue to reduce in size. Notwithstanding their relatively small size, miniaturised VGs have the potential to considerably boost microchannel heat transfer performance by increasing local heat transfer rates and preventing significant flow inversion [20–22].

An additional promising route is the supposed concept of smart and adaptive VGs. These particular VGs can be made to control their shape or position in a time-based manner in response to fluctuations in a system's flow or thermal conditions. These adaptive VGs can control the use of heat transfer applications in a way that has not been feasible before. This is on account of their ability to change in response to varying heat loads, making it possible to operate in the most effective conditions at any particular time. By using shape-memory materials or actuators, VG structures can modify their geometry to realise optimum efficiency under various operating conditions. This concept of real time adaptation is advantageous for use in extremely dynamic environments where the thermal loads can frequently change, for instance in aerospace or automotive systems [23–25].

To date, no evaluation has been conducted on the vortex generator approach used to improve thermo-hydraulic performance in thermal systems. This article examines VG techniques to improve the heat transfer in advanced thermal management systems. The study explores the developments in VG designs and materials. Similarly, it examines the optimisation methods, for example the response surface optimisation method and artificial neural networks, in conjunction with synthesising concepts from various studies, with the intention of producing next-generation heat management systems. This article also investigates the application of modest variable geometries for microchannels, adaptive variable-geometry technologies and the use of nanofluids as a working fluid. These methods are capable of improving the cooling efficiency in electronic devices, aerospace applications, as well as automotive systems. These novel approaches to scientific research and practical innovation provide a strong foundation to develop efficient and adaptive thermal management systems throughout a wide range of applications.

2. Vortex generator shapes, designs and applications

Vortex generators are critical Active Flow Control devices commonly used in thermal systems, predominantly in heat transfer applications, such as heat exchangers, micro-channel heat sinks (MCHSs), along with similar systems. By inducing vortices that promote mixing between fluid layers, VGs effectively enhance heat transfer coefficients by way of disrupting thermal boundary layers. In recent years, various VG geometries, incorporating delta, rectangular and trapezoidal winglets, have been extensively developed and modified for applications in aircraft.

This paper presents a detailed analysis of the state of the art of VG technology, including the shapes, configurations and types of material focusing on HTE together with a reduced ΔP. The combination of nanofluids and perforated VGs is also presented, providing an understanding of the different approaches that are available to enhance thermal performance. This design and review of applications presents a systematic synthesis of VGs, despite being more limited in terms of the specific configurations that boost thermal performance in a variety of industrial processes.

The techniques applied for VGs, such as delta winglets, rectangular, trapezoidal, perforated designs, shape optimisation nanofluids, along with the application of VGs in heat exchangers, thermal performance enhancement, artificial intelligence and machine learning will be discussed in detail. This will lay the foundation for further developments in thermal performance via the incorporation of high-performance cooling systems.

2.1. Delta winglet vortex generators

Delta winglet vortex generators are exceedingly popular owing to the generation of robust longitudinal vortices. This fact combined with the triangular shape of the delta winglets creates an improved performance in relation to the fluid mixing, so as to increase convective heat transfer in both laminar and turbulent flow. Research confirms that delta winglets VGs can significantly affect the performance, increasing the Nu, by up to 60 %. Hence, they are suitable for applications that require high heat transfer rates, for example electronics cooling [26–30].

Gönül, et al. [26] investigated delta winglet-type VGs in microchannels to increase heat transfer, as illustrated in Fig. 1-a. Results obtained with multi-objective optimisation employing Response Surface Methodology (RSM), determined that the crucial variables to improve heat transfer are the water inlet velocity and VG height (geometric factor). Tian, et al. [27] studied how longitudinal VGs (LVGs) affect microchannel heat transfer and ΔP, as presented in Fig. 1-b. The study ascertained that LVGs improved heat transfer by 12.3–73.8 % for certain configurations, causing a ΔP of 40.3 to 158.6 %. Oneissi, et al. [28] used VGs to evaluate heat transfer enhancement in parallel plate-fin heat exchangers (HE), as presented in Fig. 1-c. An innovative configuration, the inclined projected winglet pair (IPWP), was compared to the delta winglet pair (DWP). Both VGs exhibited similar heat transfer rates. However, the IPWP's aerodynamic design delivered a 6 % higher enhancement factor and a lower ΔP penalty. Li, et al. [29] studied delta-winglet pair vortex generators (DWPVG) on the heated wall of a semi-circular helical jacket, as shown in Fig. 1-d. The study ascertained that heat transfer enhancement is superior utilising the DWPVG, as a result of the stronger and more stable vortices, which performed successfully at angles of attack of between 25°–30°. In the research they conducted, He, et al. [30] investigated punched winglet VG arrays, as demonstrated in Fig. 1-e. Two DWP with continuous and discontinuous layouts were compared to a large winglet configuration. Their study discovered that discontinuous winglet arrays delivered the highest HTE of 70.6 %, but a ΔP of 97.2 %. Front-arranged VGs, in particular continuous arrays, performed efficiently with HTE of 81.2 % and

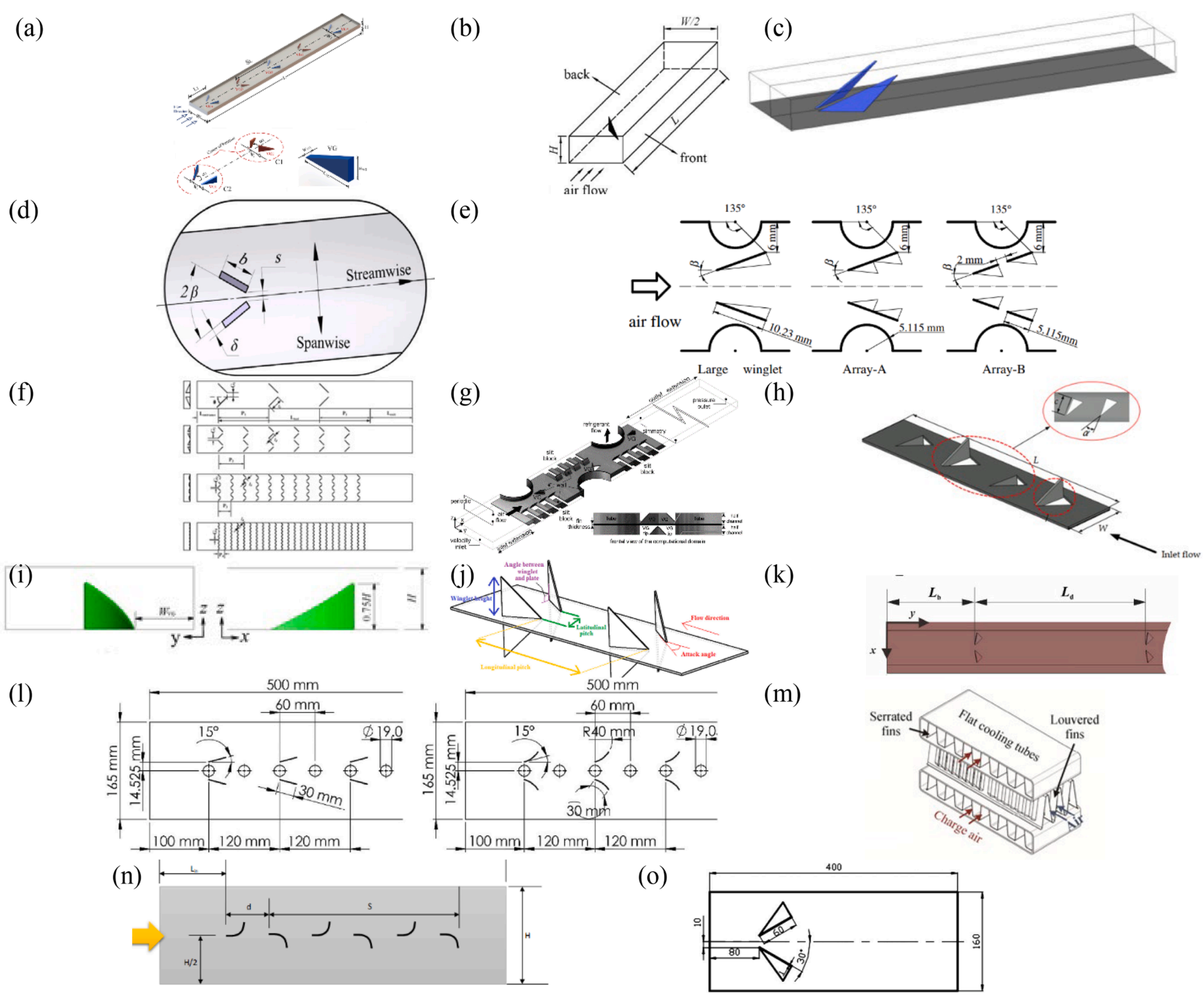

Fig. 1. Delta winglet Vortex generator, a)- Gönül, et al. [26], b)- Tian, et al. [27], c)- Oneissi, et al. [28], d)- Li, et al. [29], e)- He, et al. [30], f)- Wu, et al. [15], g)- Moreno, et al. [31], h)- Yaningsih, et al. [32], i)- Song, et al. [33], j)- Pourhedayat, et al. [34], k)- Li, et al. [35], l)- Syaiful, et al. [36], m)- Zhang, et al. [37], n)- Yousif, et al. [38], o)- Wu and Tao [39].

increase in ΔP of 135.6 %.

Wu, et al. [15] optimised delta-winglet VGs in multiple rows in a fully developed forced-convection channel. The optimal height ratio and pitch ratio were 1/6 and 16, with a COP of 1.33–1.38, as exhibited in Fig. 1-f. Multiple rows of VG improved thermal mixing and secondary flow diffusion. Moreno, et al. [31] optimised compact HE with three rows of tubes and slit fins using DWVG, as shown in Fig. 1-g. Compared to smooth slit fins, the most efficient geometry increased heat transfer by 8.74 % and ΔP by 14.77 %. The optimised design comprised a 5.08-mm module, 49.86° angle of attack and 22.51° module angle. Yaningsih, et al. [32] investigated a double-DWP, as presented in Fig. 1-h. In comparison to the plain tube, DWPs increased the Nu by 364.3 % and the f 15.5 times. Similarly, the coefficient of performance (COP) also improved attaining 1.4 using higher blockage ratios. Song, et al. [33] examined how VG shapes affect plate HE heat transfer, as exhibited in Fig. 1-i. Concave and convex curved DWPVGs were compared to a normal plane DWPVG with central angles from 10° to 80° and angles of attack from 20° to 40°. It was determined that the Nu increases through the central angle of the concave curved VG, but decreases with the convex VG. The concave curved VG revealed the highest Nu and COP

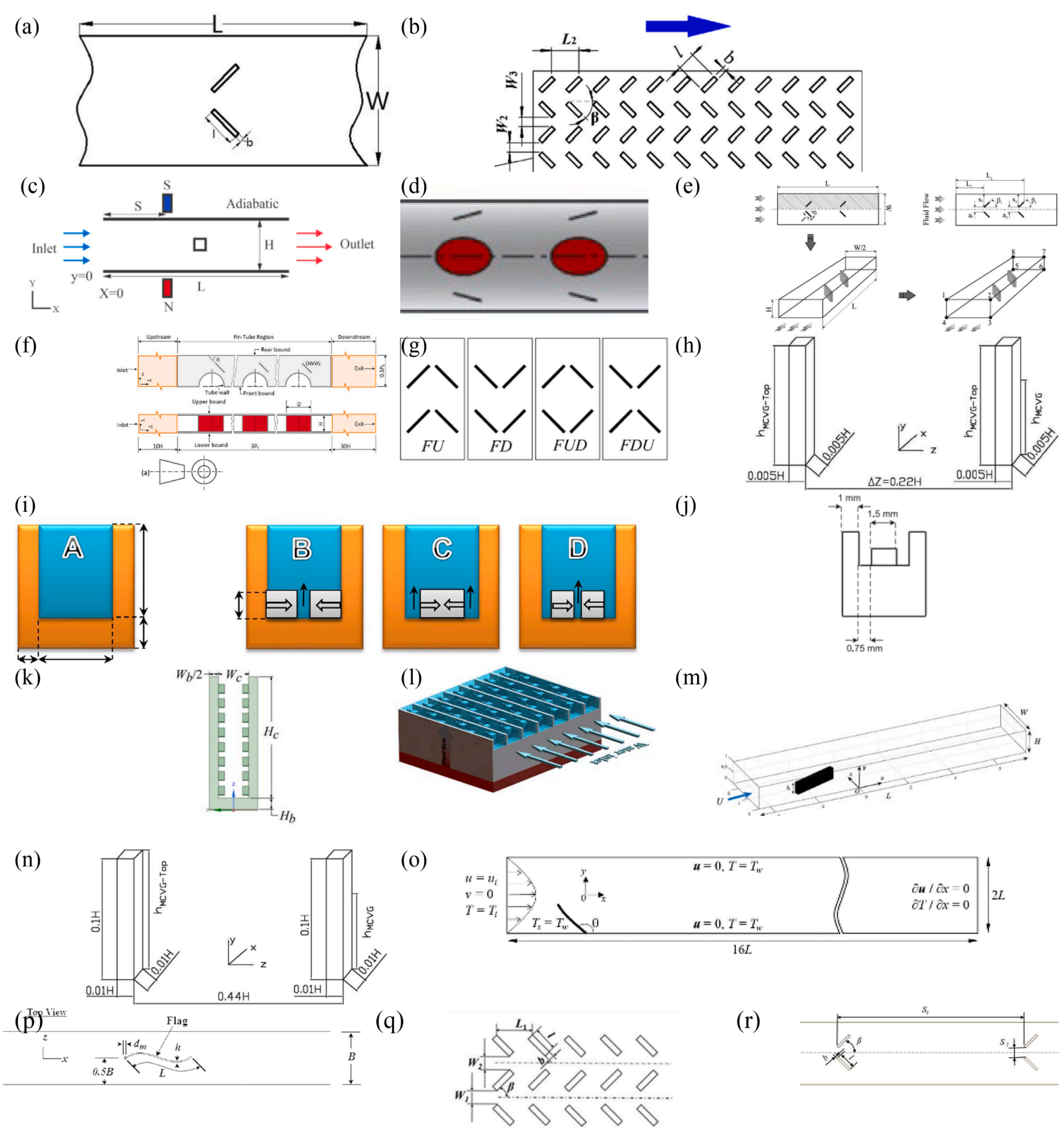

Fig. 2. Rectangular Winglet Vortex Generators: a)- Chen, et al. [40], b)- Zhang, et al. [41], c)- Jalali, et al. [42], d) Ibrahim and Alturaihi [43], e)- Ebrahimi, et al. [44], f)- Arora and Subbarao [45], g)- Zhao, et al. [46], h)- Jiao, et al. [47], i)- Al-Asadi, et al. [48], j)- Hosseinirad, et al. [49], k)- Lu, et al. [50], l)- Lu, et al. [51], m)- Yu, et al. [52], n)- Jiansheng, et al. [53], o)- Amini and Habibi [54], p)- Park [55], q)- Gallegos and Sharma [56], r)- Zhang, et al. [57].

values of 19.7 % and 11.35 % higher than the convex curved VG. Pourhedayat, et al. [34] examined the thermal and exergetic VG performance of triangular winglets, as demonstrated in Fig. 1-j. Front and rear winglet orientations, latitudinal and longitudinal pitch, aspect ratio and winglet-plate angle were studied. Smaller longitudinal pitch and aspect ratios increased the thermal performance, whereas the 20 mm latitudinal pitch increased the heat transfer. Similarly, higher winglet-plate angles reduced performance, whereas lower angles boosted the Nu. In their study, Li, et al. [35] investigated MCHS with double DWPVGs, as shown in Fig. 1-k. The NSGA-II determined the ideal design point, specifically a bottom plane angle of 90°, water flow direction angle of 45°, apex distance of 1 mm, as well as an inlet velocity of 0.8 m/s. This design improved hydrothermal performance by 128.1 % in the Nu, 72.0 % in the f and 1.89 in the COP compared to a smooth microchannel. Syaiful, et al. [36] applied DWPVGs and concave delta DWPVGs in-line and staggered configurations, as shown in Fig. 1-l. It was noticed that three pairs of staggered concave delta winglet VGs increased the convection heat transfer coefficient by 53.58 % and ΔP by 69.69 % as opposed to the baseline setup without VGs. In their research, Zhang, et al. [37] studied explored louvered fin-common flow up VGs (LF-CFUVG), as illustrated in Fig. 1-m. LF-CFUVG increases flow resistance, whilst considerably improving heat transfer. The research discovered that reduced airflow angles improve heat transfer and COP despite the greater ΔP.

Yousif, et al. [38] studied concave VGs in a fish-tail locomotion pattern, as exhibited in Fig. 1-n. It was ascertained that the heat transfer increased by 4–21.1 %, with the most appropriate result attained at d/H = 1.3. This arrangement improved the secondary flow mixing, heat transfer, along with the f smoothing fluid flow. Wu and Tao [39] established that the angles of attack related to the DWPVG increased the average Nu (Fig. 1-o). Their study revealed that the 60° plate had the highest Nu, slightly outperforming the 45° plate. However, it also exhibited a higher ΔP.

2.2. Rectangular winglet vortex generators

Rectangular winglet vortex generators (RWVGs) provide a more uniform and stable flow disruption compared to DWPVGs. Their flat, rectangular shape generates corner vortices, which improve thermal mixing in regions close to the channel walls. RWVGs are typically preferred in systems where the ΔP needs to be minimised whilst still achieving moderate heat transfer enhancement. These VGs can increase heat transfer by up to 50 %, with a relatively lower increase in the f compared to other types of VG [40–44].

Chen, et al. [40] investigated a microchannel heat sink (MCHS) with LVGs, as shown in Fig. 2-a. Pertaining to height of the MCHs, the LVG heights were 1/4, 3/4 and 1, respectively. The results proved that the heat transfer performance improved by 12.3–73.8 % for the MCHs with an aspect ratio of 0.0667 and 3.4–45.4 % for an aspect ratio of 0.25. Nonetheless, pressure losses increased by between 40.3–158.6 % for the smaller aspect ratio and 6.5–47.7 % for the larger. Zhang, et al. [41] optimised heat transfer with LVGs in microgaps, as shown in Fig. 2-b. The results denote that increasing the transverse spacing of the LVG pair improves flow resistance and heat transfer. Larger microgaps have a lower ΔP, although no increase in heat transfer. The microgap's ΔP and heat transfer coefficients increase with the addition of further LVG pairs.

Jalali, et al. [42] improved the formation of vortices by placing a bluff body with a steady magnetic field in a microchannel that was filled with a 2 % ferrofluid, as explained in Fig. 2-c. A 30 % increase in heat transfer efficiency and an 11 % decrease in ΔP were achieved by improving flow mixing and velocity distribution. Ibrahim and Alturaihi [43] explored the use of VGs to boost heat convection in oval tube banks for both single- and two-phase flows, as seen in Fig. 2-d. Heat transfer was enhanced by both rectangular and delta winglets, with the latter shown to be the most effective. Water velocity enhanced heat transfer by 9.15 % in the single-phase flow, whereas the delta winglets outperformed the rectangular winglets in the two-phase flow on account of the additional mixing and heat transfer.

Ebrahimi, et al. [44] investigated rectangular MCHS with five LVG configurations and different angles of attack, as presented in Fig. 2-e. It was determined that LVGs increased the Nu by 2–25 % and the f by 4–30 %. Arora and Subbarao [45] optimised finned-tube HE VGs' spatial positioning and the attack angle in relation to energy efficiency, as exhibited in Fig. 2-f. The study examines how geometric variations affect flow and thermal properties, particularly heat transfer over tube wakes. It was established that VGs with aspect ratios of 0.85 for 15° and 30° angles of attack, 1.0 and 1.2 for 45° and 60° angles of attack, respectively, are optimal. Zhao, et al. [46] examined how VGs affect motor coil heat transfer, focusing on angles of attack and transverse and longitudinal generator distances, as shown Fig. 2-g. It was confirmed that VGs with a 45° angle of attack are the most effective. Additionally, it was demonstrated that the flow-Down with a longitudinal distance of 4 h is optimal, whilst the Flow-Up with the same distance runs better at a higher Re. Jiao, et al. [47] calculated heat transfer and flow in a channel with miniature cuboid VGs (MCVGs), as exhibited in Fig. 2-h. It was ascertained that in the transition area, MCVGs have a COP greater than 1, whereas MCVGs in the viscous sublayer have a COP below 1. The transition area is where the MCVGs perform most efficiently, increasing the COP by 8.15 %. It should be mentioned that the f drops by 8.05 %, whereas the Nu grows by 5.17 %.

Al-Asadi, et al. [48] examined how gaps along cylindrical VGs in a MCHS improve heat transfer and ΔP, as observed in Fig. 2-i. Their study determined that the end gaps alone increase heat transfer and reduce the ΔP, achieving a COP of 1.0 as opposed to 0.7 for full-span VGs. End gaps create longitudinal vortices that direct hot fluid from channel side walls into bulk flow, improving heat transfer. Hosseinirad, et al. [49] examined mini-channel fluid flow and thermal performance using non-uniform transverse VGs (TVG), as explained in Fig. 2-j. Long TVGs mixed fluid better than short ones. As the Re rose, TVGs developed 3D swirl flows that encouraged heat transfer. Thermal performance increased with long TVGs upstream, although the ΔP dropped. Long-to-short TVG layouts displayed the greatest Nu and f ratios (0.63 and 2.06). Lu, et al. [50] studied rectangular VGs in a rectangular microchannel, as shown in Fig. 2-k. With effective cooling, the "co-flow-down" configuration saved over 78.8 % of the pumping power. Heat transfer without the ΔP was efficient with VG parameters with a height ratio of 0.2 and an angle of attack of 45°.

Lu, et al. [51] studied how LVGs improve heat transfer in 3D stacked chip micro gaps, as exhibited in Fig. 2-l. Compared to smooth channels, LVGs significantly improve cooling performance, reducing wall temperature by 14.49 °C at 41 W/cm^2 and 112 ml/min. Owing to stronger vortex interaction, closer LVG spacing cools but increases the ΔP. Yu, et al. [52] considered how a rectangular VG affects channel flow-induced particle resuspension, as shown in Fig. 2-m. VG-induced vortices increased particle removal forces and resuspension rates in long, strip-like regions with reduced boundary-layer thickness, specifically when the VG was installed at a greater angle of attack. Higher surface-averaged removal forces and resuspension rates improved particle removal, notably for micron-scale particles that are difficult to disturb in VG-less channel flows. Jiansheng, et al. [53] investigated VG configurations using cuboids to improve heat transfer and thermal performance, as presented in Fig. 2-n. It was established that interrupted wavy mini-channels with nanofluids outperform traditional designs thermally.

Amini and Habibi [54] established that flexible splitter VGs improved heat transfer and hydrothermal performance by 190 % and 10 %, respectively, compared to a clean channel, as shown in Fig. 2-o. Park [55] realised that self-sustained oscillating flexible VGs disrupted the thermal boundary layer and improved fluid mixing, boosting heat transfer, as illustrated in Fig. 2-p. The system performed efficiently at an inclination angle of 0.8π, resulting in larger vortices during flapping transitions. Gallegos and Sharma [56] tested rectangular channels with a flapping flag VG, as depicted in Fig. 2-q. The flapping flag increased flow unsteadiness and turbulence, increasing the Nu by 1.34 to 1.62 times compared to bare channels. The flag's oscillation mode and frequency increased the f 1.39 to 3.56 times. In their study, Zhang, et al. [57] optimised flow and heat transfer in a rectangular microchannel with LVGs, as presented in Fig. 2-r. The study determined that the Nu was noticeably affected by the LVG pair number and spacing, while flow resistance was affected by the length of the LVG. Design optimisation increased the Nu by 23.6 % and efficiency by 7.2 %.

2.3. Trapezoidal vortex generators

Trapezoidal vortex generators are an advanced design that combines the advantages of delta and rectangular winglets. Their tapered shape permits smoother flow disruption creating greater control as regards both heat transfer and pressure loss. Studies indicate that trapezoidal VGs outperform rectangular ones in terms of thermal performance, particularly when the front width is greater than the back width. Trapezoidal VGs are particularly suited for high heat flux applications, with COP improvements of up to 1.75 [58–60].

In the study they completed, Heydari, et al. [14] studied micro pin-fins and micro VG for high-heat flux device heat transfer, as depicted in Fig. 3-a. It was examined the thermal and hydraulic performance of Co- and Counter-rotating VGs and parallel micro pin-fins. It was determined that multiple micro VGs and micro pin-fins improved system performance more than using each separately. The number and spacing of pin-fin pairs affected performance. Zheng, et al. [58] investigated how trapezoidal LVGs could improve heat transfer in MCHS, as explained in Fig. 3-b. The study established that trapezoidal LVGs outperform rectangular ones in thermal performance, particularly when the front width (a) is bigger than the back width (b), and the height (h) is half the channel height. The optimal parameters were $a = 0.6$ mm, $b = 0.3$ mm and h = 0.75 mm, attaining a COP of 1.756. Karkaba, et al. [59] optimised trapezoidal VGs by utilising the angle of attack, roll angle, base angles, height, length and shape length, as illustrated in Fig. 3-c. The optimised VG design outperformed previous designs by 14 % and improved thermal enhancement by 35 % as opposed to an empty channel. Das and Hiremath [60] examined how butterfly-wing VGs affect thermos-hydraulic performance and entropy generation in rectangular microchannels, as shown in Fig. 3-d. Their investigation determined that the butterfly-wing VGs outperformed plain microchannels in convective heat transfer (10–26 %), ΔP (3–14 %), and total entropy generation (3–16 %).

Syaiful, et al. [61] ascertained that VGs made of perforated concave rectangular winglets (PCRWs) and rectangular winglets (RW), as exhibited in Fig. 3-e, reduced the ΔP by 15.38 % and 7.69 %, respectively. It was ascertained that the heat transfer performance decreased by 1.02 % for the PCRW and 4.06 % for the RW. However, their synergy angles at the highest flow velocities were 0.41° and 0.25°, respectively, signifying a strong vortex intensity and effective heat transfer. Lotfi, et al. [62] examined a new smooth wavy fin-and-elliptical tube heat exchanger with three VGs: rectangular trapezoidal winglet (RTW), angle rectangular winglet (ARW), in addition to a curved angle rectangular winglet (CARW), as shown in Fig. 3-f. Heat transfer improved with a higher Re, wavy fin heights and lower tube ellipticity ratios, whereas the CARW and RTW VGs were outstanding at smaller and larger angles of attack.

Das and Hiremath [63] studied a butterfly-wing VG in a MCHS (1 mm width, 0.63 mm height, 50 mm length), as shown in Fig. 3-g. Various variables were tested: different widths (0.24–0.48 mm), wing heights (0.2–0.5 mm), wing lengths (1–3 mm), and Reynolds numbers (Re) (142–544). Their study ascertained that the greatest parameters were 0.48 mm wider, 0.12 mm narrower. They also comprised a wing length of 1 mm, a wing height of 0.38 mm and a Re of 544, resulting in a COP of 1.35.

2.4. Perforated vortex generators

Perforated vortex generators introduce a novel approach by incorporating holes in the VG structure, permitting fluid to pass through. This design reduces the ΔP commonly associated with solid VGs while maintaining or enhancing the heat transfer performance. Perforated VGs can decrease pressure loss by up to 25 %, making them ideal for systems where fluid flow resistance must be minimised, for example in compact heat exchangers or microchannel heat sinks [64–68].

Wang, et al. [64] investigated perforated rectangular winglet VGs in minichannels to improve heat transfer, as described in Fig. 4-a. The study comprised punching indexes of 0.05, 0.10, 0.20 and 0.40, together with pitches of 15 mm, 30 mm and 45 mm. The topology and intensity of downstream mixed vortices were significantly affected by VG hole parameters. Jet flow increased with punching index values reducing the mixed vortices and heat transfer efficiency, whilst increasing the

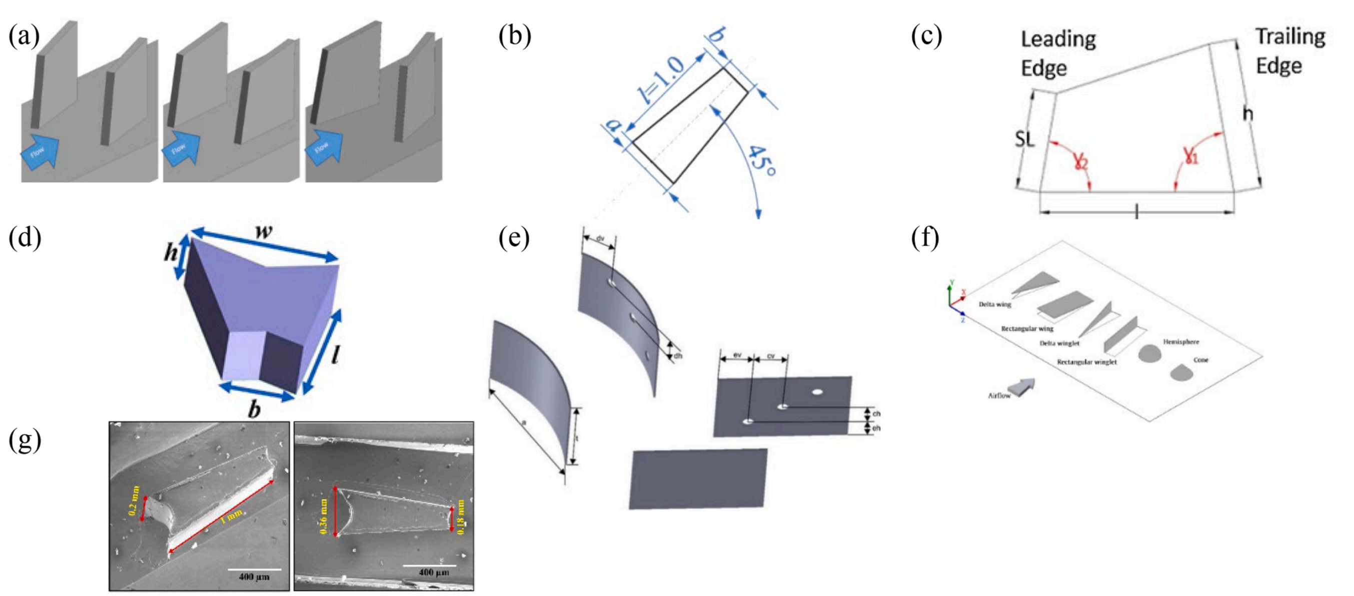

Fig. 3. Trapezoidal Vortex Generators: a)- Heydari, et al. [14], b)- Zheng, et al. [58], c)- Karkaba, et al. [59], d)- Das and Hiremath [60], e)- Syaiful, et al. [61], f)- Lotfi, et al. [62], g)- Das and Hiremath [63].

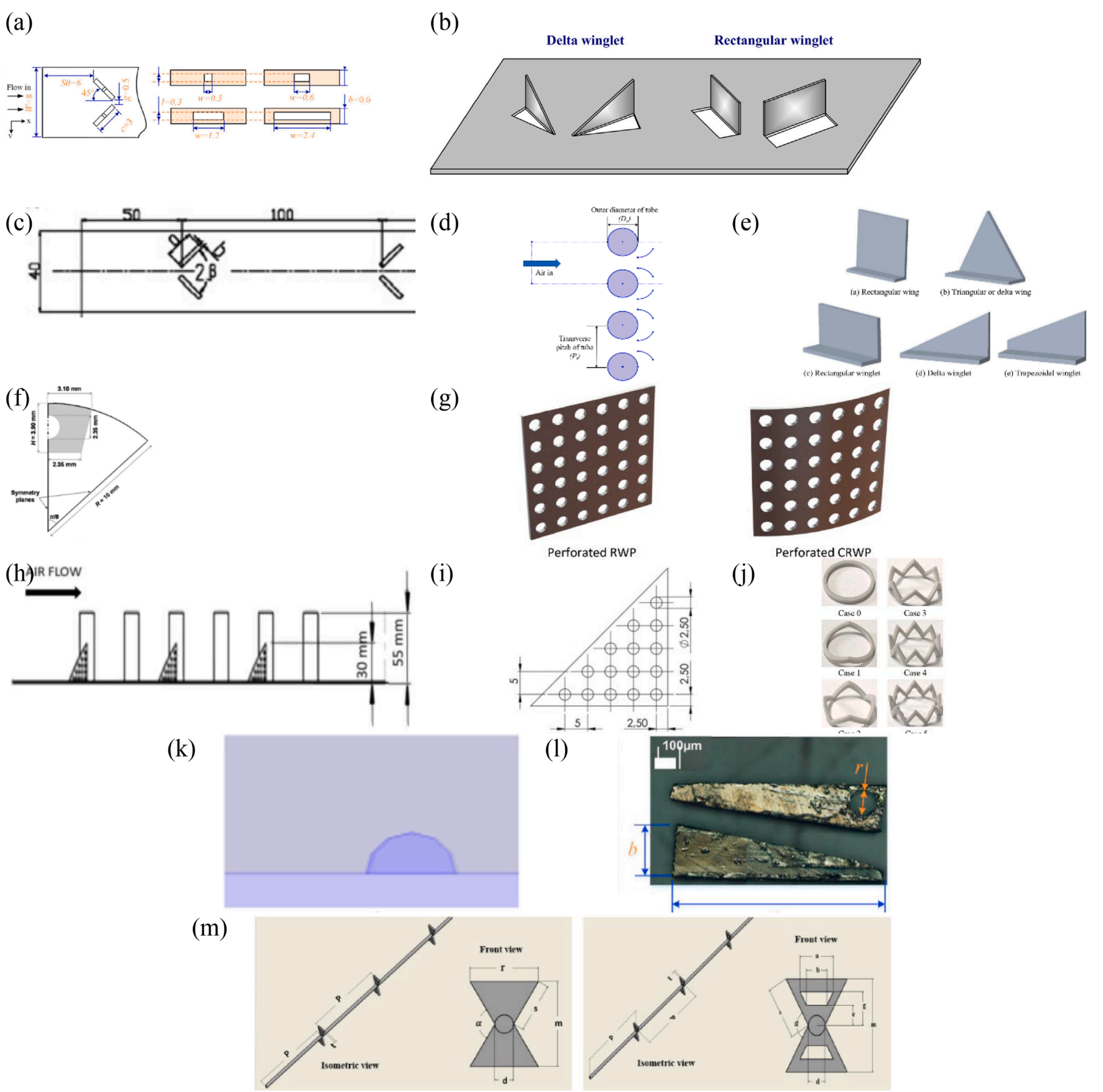

Fig. 4. Perforated Vortex generator: a)- Wang, et al. [64], b)- Skullong, et al. [65], c)- Ma, et al. [66], d)- Saini, et al. [67], e)- Modi, et al. [68], f)- Habchi, et al. [69], g)- Heriyani, et al. [70], h)- Syaiful, et al. [24], i)- Syaiful, et al. [71], j)- Wu, et al. [21], k)- Al-Asadi, et al. [72], l)- Wang, et al. [25], m)- Sudheer and Madanan [73].

pressure losses. Skullong, et al. [65] investigated vortex flows using rectangular VG and trapezoidal VG with relative heights (BR = 0.2 and 0.48), longitudinal pitch ratios (PR = 1, 1.5, and 2), and a fixed angle of attack of 30°, as represented in Fig. 4-b. The rectangular VG with BR = 0.48 and PR = 1 had 7.1 and 109.5 times the heat transfer and f of the flat duct. The TVG with BR = 0.2 and PR = 1.5 demonstrated the most effective thermal performance of 1.84. Perforated rectangular and trapezoidal VGs with hole diameters of 1, 3, 5 and 7 mm, respectively, were tested to reduce pressure loss. The perforated rectangular VG with a 1 mm hole had the greatest heat transfer and f, 6.78 and 84.32 times higher than the smooth duct, while the perforated trapezoidal VG with a 5 mm hole revealed the most efficient thermal performance of 2.01.

Ma, et al. [66] investigated VG configurations to improve system heat transfer, as portrayed in Fig. 4-c. Microchannels with LVGs revealed a higher heat transfer (2–25 % in the Nu) and f (4–30 %), as opposed to those without LVGs. The study showed that curved DWPVGs showed that more punched holes improved heat transfer but increased the ΔP. It was observed that six-hole curved trapezoidal winglet VGs improved heat transfer. Saini, et al. [67] studied fin-and-tube-HE with curved DWPVGs, as well as different numbers of circular holes, as shown in Fig. 4-d. They ascertained that the 6-hole configuration reduced the f and increased the Nu by 77.25 % compared to those without VGs. Modi, et al. [68] investigated the thermo-hydraulic performance of fin-and-tube-HE VGs, as presented in Fig. 4-e. The study examined VGs with 1, 2, 4 and 6 punched holes. It was determined that VGs with punched holes improved performance, with the 6-hole configuration comprising the highest Nu increases (45.95 % at a Re of 400 and 57.37 % at a Re of 2000) and f reductions of 13.81 %.

Habchi, et al. [69] investigated perforated trapezoidal (PTVG), as presented in Fig. 4-f. PTVG configurations in direct and inverse flow and tab array arrangements in a circular pipe were compared. It was discovered that the heat transfer was 40 %−80 % higher than an empty pipe without increasing the pumping power. Their study confirmed that perforations reduce ΔP and maintain heat transfer. Heriyani, et al. [70] noticed in-line perforated concave rectangular winglet pair VGs (PCRWP VGs), as depicted in Fig. 4-g. Furthermore, they confirmed that PCRWP VGs had a lower cost-benefit ratio of 3.56 than staggered ones. The COP improved by 1.29, revealing that PCRWP VGs improve heat transfer while controlling ΔP. Syaiful, et al. [24] studied three-row perforated convex delta winglet pair VGs, as explained in Fig. 4-h. They explained that the Nu increased by 1.5, whilst the f ratio increased by 1.4. Convex delta winglets improved heat transfer and air thermal resistance, resulting in a COP of virtually 1.3. Syaiful, et al. [71] determined that concave delta winglets without holes at a *Re* of 9000 included the highest COP of 1.42, as depicted in Fig. 4-i. The lowest cost-benefit ratio was 1.75 with three pairs of vortex generators at a *Re* of 3500.

Wu, et al. [21] proposed a multi-V-winglets VG to improve thermal and fluid flow, as presented in Fig. 4-j. They determined that as the winglets increase, the heat transfer improves but the f decreases. Holes in the winglet surfaces created jet flows, reducing the f and improving the local heat transfer. The study established 130.57–156.42 % Nu improvements from VG pitch. The optimal setup with 8 winglets, outer surface holes, and a 25 mm pitch had a maximum COP of 2.83. Al-Asadi,

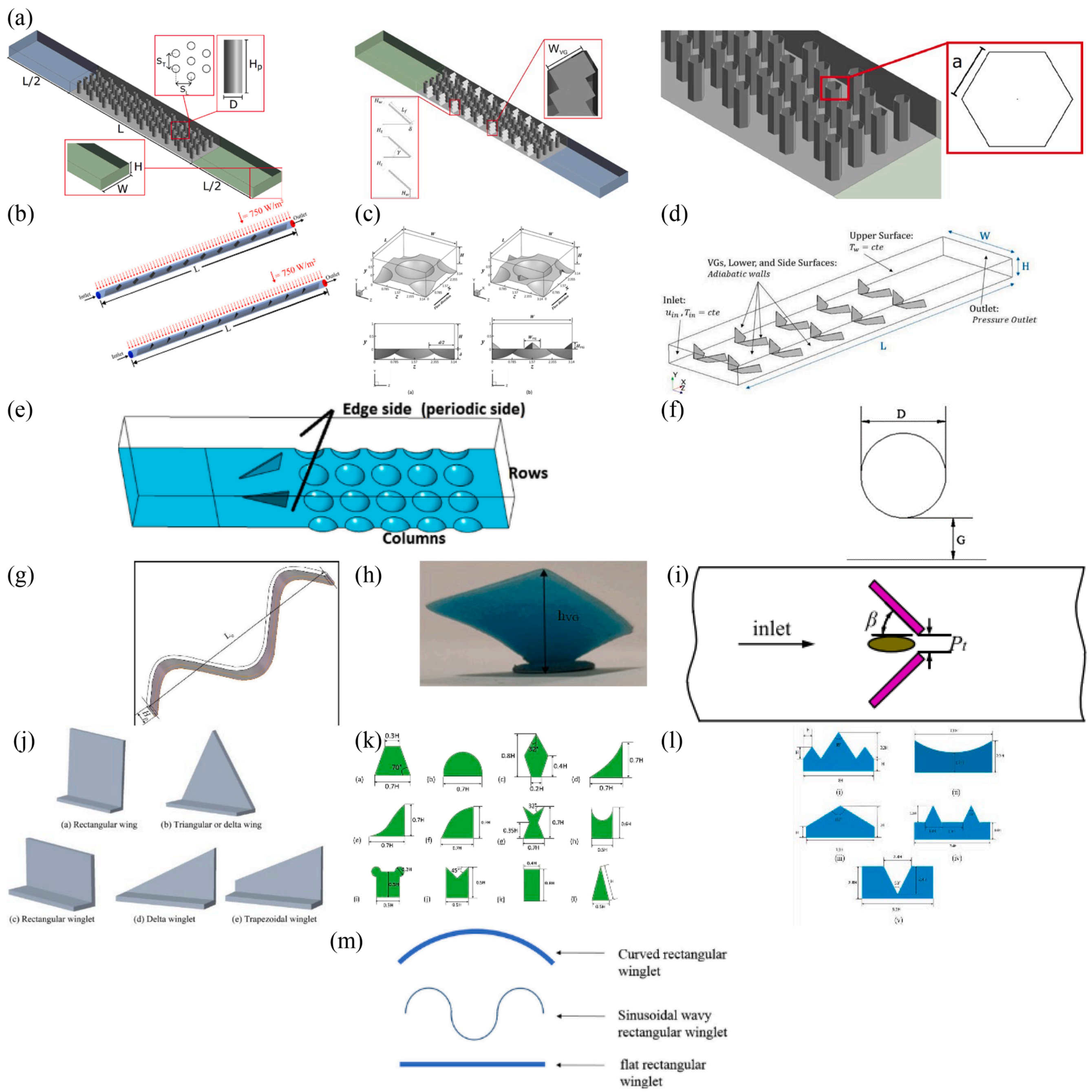

Fig. 5. Other designs with a vortex generator: a)- Aguirre, et al. [74], b)- da Silva, et al. [75], c)- Yang, et al. [76], d)- Karkaba, et al. [77], e)- Luo, et al. [78], f)- Wang and Zhao [79], g)- Wu, et al. [80], h)- Dogan and Erzincan [81], i)- Tang, et al. [82], j)- Modi and Rathod [83], k)- Hasan, et al. [84], l)- Fahad, et al. [85], m)- Modi and Rathod [86].

et al. [72] investigated perforated VGs in MCHS with quarter-circle and half-circle cross sections, as exhibited in Fig. 4-k. The research explained that these VGs can improve heat transfer to cool smaller and lighter electronic devices using COP. Wang, et al. [25] considered delta winglet VGs with holes in MCHS, using two VG arrangements on opposite walls and varying hole diameters (0.05, 0.15, 0.25 mm) and pitch values (15, 30, 45 mm), as observed in Fig. 4-l. They discovered that increased hole area suppressed vortex shapes downstream of the VGs, with ICVs possibly disappearing at a hole diameter of 0.25 mm. Case 1 with the right angle of the triangular wing near the centre of the channel, had the highest COP value. Nonetheless, the holes reduced the COP by 0.2 %−6.9 % and 0.1 %−8.3 %, respectively. Sudheer and Madanan [73] analysed VGs using butterfly designs for square MCHs, as described in Fig. 4-m. Their research confirmed that lowering the pitch spacing from 10 to 5 mm enhanced heat transfer by 15.08–46.39 %. Moreover, butterfly insert wing perforations lowered the heat transfer performance by 5.07–16.17 % and f by 4.01–20.78 %. Essentially, it was proven that inserts without perforations performed better.

2.5. Shape optimisation of vortex generators

Microchannel heat sinks (MCHSs) are essential components in high-performance cooling systems, particularly in applications such as electronics cooling, turbine engines and solar collectors. To enhance heat transfer while minimising ΔP, VGs have been incorporated into MCHSs to improve fluid mixing, disrupt boundary layers and reduce thermal resistance. Recent studies have also explored the use of novel VG shapes, nanofluids and geometrical modifications, for example dimples and trapezoidal winglets, to further heighten heat sink performance [74–77].

This section reviews recent research on the use of VGs and shape modifications in MCHS systems. The studies investigate the effects of VG shapes, such as delta winglets, rectangular winglets and trapezoidal configurations, along with the pin shape alterations. The findings underline the significant improvements in heat transfer, ΔP, along with thermal performance, providing practical information into the potential of these technologies to optimise MCHS design to achieve better efficiency and cooling performance. Aguirre, et al. [74] examined the effects of VGs, pin shape modifications and shear-thinning nanofluids' on MCHS, as depicted in Fig. 5-a. They established that VGs increased ΔP and heat transfer rates by over 20 % in Newtonian fluids. VGs reduced pumping costs by 20 % in shear-thinning fluids, improving heat sink performance without increasing ΔP. In their study, da Silva, et al. [75] examined how LVGs improve flat-plate solar collector heat transfer, as presented in Fig. 5-b. The research evaluates delta-winglet and rectangular-winglet VGs at *Re* of 300, 600 and 900 and angles of attack of 15°, 30° and 45°. Both types of VGs improve heat transfer, with the rectangular-winglet exhibiting the most improvement at 45°. At a 30° angle, the delta-winglet attains the most effective balance between HTE and ΔP penalty. The VGs create secondary flow, with the rectangular-winglet generating corner vortices, while the impact of the delta-winglet's heat transfer is evident even when removed with minimal loss.

Yang, et al. [76] investigated the flow and heat transfer of a new dimple cooling channel with wedge-shaped VGs, as shown in Fig. 5-c. The dimple's recirculating flow region should have better flow mixing and heat transfer. The cooling channel-VG width ratio is the main design parameter. The stronger counter-rotating vortex downstream improves heat transfer as width ratio increases. The volume goodness factor increases by 30 % in contrast to a standard dimple cooling channel when the width ratio = 0.4411. Karkaba, et al. [77] studied convective heat transfer with multiple VG rows with different longitudinal pitches (LP), as explained in Fig. 5-d. It was determined that the optimal configuration (five VG rows with LP = 3H), improves thermal enhancement by 69 % at *Re* = 2000 and 90 % at *Re* = 10,000 compared to an empty channel. Luo, et al. [78] examined how dimples and DWPVGs affected flow structure, heat transfer and f, as described in Fig. 5-e. A baseline channel together with DWPVGs was compared to inline and staggered dimple arrangements. The dimples interact with the DWPVG to significantly affect flow structure. Compared to the baseline, inline dimples increased the heat transfer by 36.23 % and f by 36.29 %. Inline dimples achieved the most effective mixing and heat transfer, boosting thermal performance by 28.50 %.Wang and Zhao [79] explained that a small circular cylinder VG improves rectangular channel heat transfer, as explained in Fig. 5-f. The gap ratio (G/D) between the cylinder and channel bottom is crucial, with the greatest improvement at 2.0. At this ratio, the cylinder's wake and wall boundary layer maximise heat transfer, increasing the Nu by 18.76 %.

Wu, et al. [80] studied a sinusoidal wavy winglet VG to improve fin-and-tube HE air-side heat transfer, as revealed in Fig. 5-g. The study ascertained that wavy VGs improve convective heat transfer by generating longitudinal vortices and local secondary flows. The results reveal that the Nu ratio is 1.09–1.52, the f is 1.09–2.31, and the surface goodness is 1.061.24. Dogan and Erzincan [81] investigated VGs which were symmetrically placed on the channel base, as demonstrated in Fig. 5-h. The most effective COP was a transverse pitch ratio of 0.16. For inline vortex arrangements with a constant transverse pitch ratio, a longitudinal pitch ratio of 1.5 produced the highest COP of 1.59. It is worth noting that the inline arrangement worked better than the staggered. Tang, et al. [82] modified LVGs using rectangular and delta winglets with elliptical poles, as illustrated in Fig. 5-i. It was proven that each of the LVG configurations reduced the velocity-temperature gradient angle compared to the smooth channel.

Modi and Rathod [83] tested modified RWPVGs, as presented in Fig. 5-j. They established that RWPVGs improved the heat transfer coefficient compared to experiments without RWPVGs, although the ΔP increased. Comparative studies at 65 °C, 75 °C and 85 °C showed that the RWPVGs with a circular punched hole outperformed the flat RWPVGs by 1.04–10.52 %. Hasan, et al. [84] studied wing-type VG shapes examined at a forward inclination of 135° for optimal vorticity, as portrayed in Fig. 5-k. The kite-shaped VG cooled best. Gothic type VGs with a 3 mm pitch distance cooled efficiently in arrays with five pitch distances, improving cooling by 11 % in comparison to a single VG. Gothic VGs reduced the outlet temperature by 12 % more than the discrete ribbed and 4 % more than the perforated louvered strip VGs. Fahad, et al. [85] explored five new VG designs, as shown in Fig. 5-l. They discovered that a VG with three top triangles delivers the most effective thermal performance, increasing the Nu by 38.2 % and f by 80.38 %. It attains the highest thermal COP, which is 1.63 % higher than the rectangular VG. Modi and Rathod [86] studied fin-and-tube compact heat exchangers with sinusoidal wavy and elliptical curved RWPVGs, as shown in Fig. 5-m. Both wavy and elliptical curved VGs improve heat transfer. The wavy-up configuration was observed to be the most effective. In terms of each of the configurations, the *Re* increases the Nu, with the wavy-up RWPVGs having the highest values.

Yang, et al. [87] studied the use of a ring-shaped Karman-VG (KVG) with a total divergence angle of 36°, as presented in Fig. 6-a. A KVG diameter (D) of 3–4 % of the expansion section length, 7.5–10.0 D from the throat and 2.0–3.0 D from the wall is recommended. Well-designed KVGs create Karman vortex streets that improve flow mixing and suppress flow separation, improving pressure recovery. Al-Asadi, et al. [88] researched the effects of circular, triangular and rectangular VGs, as depicted in Fig. 6-b. It was established that circular VGs performed successfully in heat transfer tests, suggesting they could improve thermal management in compact electronic devices. Raihan, et al. [89] examined cylindrical VGs, as demonstrated in Fig. 6-c. VG positions (front, middle, back), radius (100–300 μm), and distance (0–500 μm) were studied. Their study showed that placing VGs at the front of the MCHS with no spacing and a radius of 300 μm resulted in the lowest thermal resistance but the highest pressure penalty. The highest COP was achieved with VGs at the front, a 100 μm radius and no spacing.

Linardos, et al. [90] investigated heat transfer in pipes using three

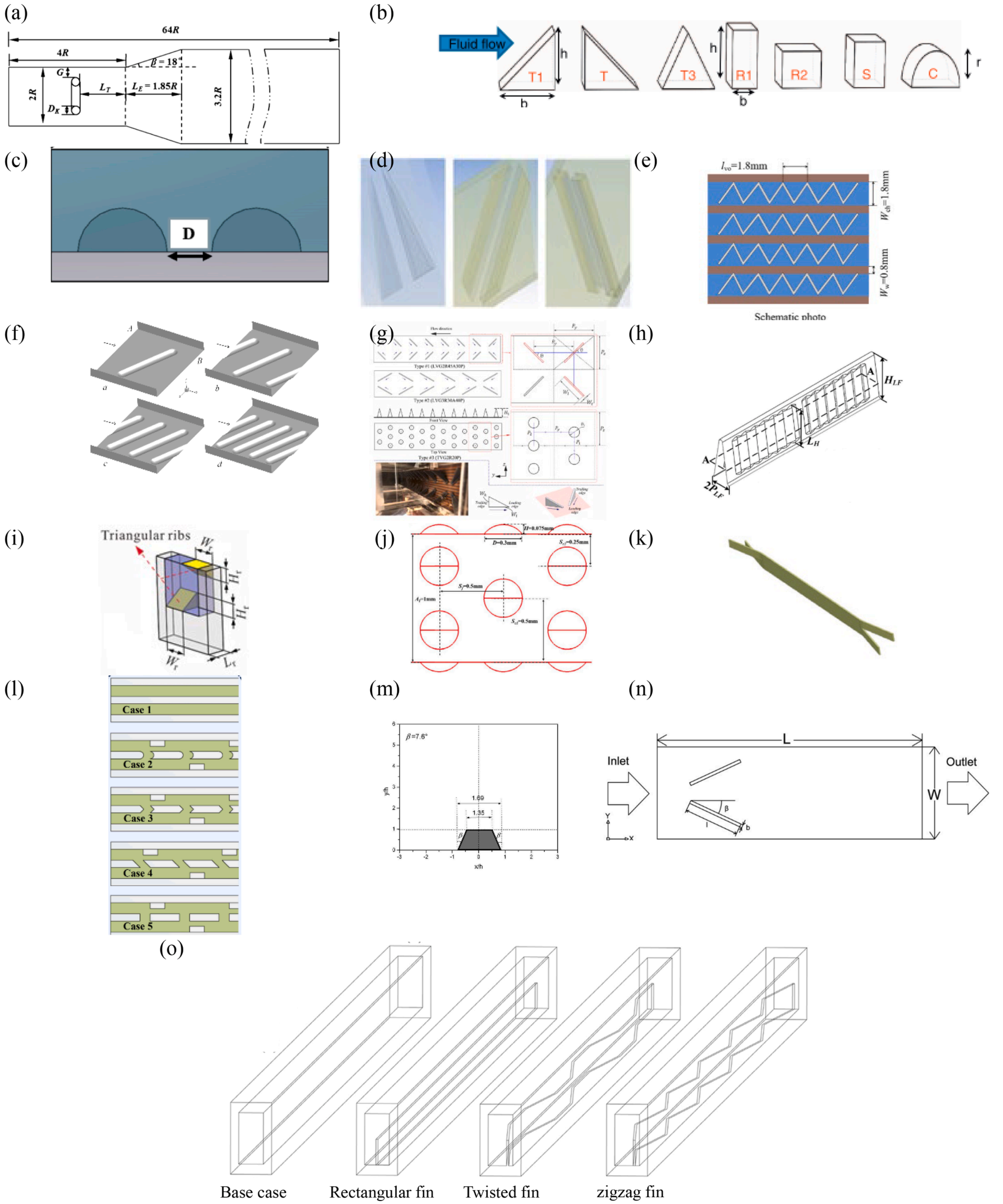

Fig. 6. Other designs: a)- Yang, et al. [87], b)- Al-Asadi, et al. [88], c)- Raihan, et al. [89], d)- Linardos, et al. [90], e)- Lu, et al. [91], f)- Isaev, et al. [92], g)- Zhao, et al. [93], h)- Zhang, et al. [12], i)- Feng, et al. [94], j)- Chen, et al. [95], k)- Feng, et al. [96], l)- Du, et al. [97], m)- Lemenand, et al. [98], n)- Liu, et al. [99], o)- Ali, et al. [100].

unique interior designs: two using Longitudinal Vortex Generators (LVG) to channel fluid from the centre to heated walls and one Batch Heated and Channelled Pipe (BHCP) that separated fluid near the walls to maximise heating, as illustrated in Fig. 6-d. The mean Nu increased by 260 % for the Batch Heated and Channelled Pipe (BHCP), indicating outstanding heat transfer efficiency. However, the substantial pressure loss implies that further improvements are necessary.

Lu, et al. [91] employed a helix-shaped VG to improve heat transfer in MCHS subcooled flow boiling, as described in Fig. 6-e. With an 8.4-fold increase in the heat transfer coefficient and a 21.8 % increase in critical heat flux, the VG improved heat transfer. Isaev, et al. [92] studied oval-trench dimples placed on the heated wall of a rectangular narrow channel, inclined at 65° to the incoming flow, as shown in Fig. 6-f. The separated flow zone's f decreased 4-fold, whilst the heat transfer increased 6.5-fold when the dimple step was reduced from 8 to 2. Zhao, et al. [93] investigated LVGs and TVGs in a serpentine channel in relation to heat transfer, as exhibited in Fig. 6-g. They ascertained that LVGs improve heat transfer more than TVGs, although both improved the average Nu compared to a smooth endwall. The most effective LVGs configurations comprise a 45-degree angle, aspect ratio of 2 and 0.02 m pitch, increasing the Nu and thermal performance by 35 and 26 %, respectively. Zhang, et al. [12] explored the louvered fin-common flow up vg (LF-CFUVG), as presented in Fig. 6-h. The LF-CFUVG exhibited a higher flow resistance than the baseline LFHE due to reduced free flow areas and low-speed wake zones from the VGs generators. The LF-CFUVG generated longitudinal vortices that homogenised the temperature field and increased airflow, generating improved heat transfer.

Feng, et al. [94] studied MCHS with a staggered triangular rib, as described in Fig. 6-i. Their study revealed that increasing the rib width/channel width and rib height/channel width improved the thermal performance and reduced entropy generation. The most effective configuration was located at a rib width/channel width of 0.5, with the highest COP observed to be 1.502. Chen, et al. [95] investigated supercritical methane heat transfer and flow in a square mini-channel with a dimple array to improve LNG thermal performance in mini-channel heat exchangers, as shown in Fig. 6-j. A dimple channel demonstrated more effective heat transfer than a smooth channel, with only a slight increase in flow f. The VG enhancement method improved the turbulent kinetic energy generated by the dimple structure. Feng, et al. [96] investigated the effect of a new insertion-type of LVG, as illustrated in Fig. 6-k. It was established that MCHs with ITLVGs exhibit an average increase in f of 85.5 %−246.1 % and a Nu ranging from 39.2 %−102.0 %, when compared with smooth MCHs. In relation to most *Re*, the 20 mm LVG arranged in a downstream, midstream and upstream configuration demonstrates the highest COP value of 1.50. Du, et al. [97] considered how MCHS and VGs improve cooling performance with slant rib-elliptical groove-quatrefoil rib spoiler components, as depicted in Fig. 6-l. Compared to traditional designs, this design reduced the temperature and thermal resistance and improved the Nu and uniformity of the temperature. It is also determined that secondary channels and rib combinations increased heat transfer efficiency and energy savings in single crystal diamond MCHs.

In their research, Lemenand, et al. [98] examined VGs, for example delta and rectangular winglets to improve cooling system thermal performance, as shown in Fig. 6-m. Microencapsulated phase change materials (MEPCMs) with VGs boosted heat transfer at lower Re. Moreover, VGs increased the ΔP and heat transfer in flat-plate and manifold MCHSs. Their study revealed that VG configurations and dimple arrangements can optimise heat transfer. Liu, et al. [99] investigated advanced designs, in addition to the optimisation of MCHSs, as portrayed in Fig. 6-n. It was discovered that water-based MEPCMs improved thermal performance in MCHS, notably at a lower *Re*. Similarly, single crystal diamond microchannels with secondary channels and rib combinations were also developed to improve heat transfer and energy efficiency. Furthermore, film cooling with VGs, such as delta winglets and micro ramps, was also investigated. The result obtained demonstrated improved coolant coverage and cooling.

Ali, et al. [100] researched the effects of rectangular, twisted and zigzag fins inserted into regular rectangular microchannel heat sinks, as illustrated in Fig. 6-o. It was reported that the twisted fins enhanced the cooling performance, while the zigzag fins provided the most effective thermal performance.

2.6. Nanofluid with vortex generators

Thus, the combined effect of the nanofluids with vortex generators has the potential to be a potent combined method to improve the heat transfer conditions. Nanofluids, which include nanoparticles dispersed in a base fluid, possess higher thermal conductivity than that of the conventional fluids. The inclusion of nanofluids together with vortex generators, significantly increases the heat transfer rates and the coefficient of heat transfer in comparison to conventional fluids. It was established that the addition of Al_2O_3 or CuO nanofluids in VGs could generate improvements in heat transfer of up to 30 %. The combination of nanofluid and VG is extremely beneficial in applications that demand a high heat transfer rate, e.g., electronics cooling and high performance heat exchangers [101–106].

Farrokhi Derakhshandeh and Gharbia [13] examined how VGs and magneto-hydrodynamics (MHD) affect nanofluid thermal performance in MCHS, as explained in Fig. 7-a. With nanoparticle volume fractions from 0 to 7 % and a magnetic field strength of 0.05 T, the gap ratio (GR) between the cylinder and channel wall ranged from 0.5 to 4.0. The MHD and VG improved heat transfer by 6.5 %−17.70 %, respectively. The overall efficiency increased by 2.55–29.05 % for water-Al_2O_3 and 9.78–50.64 % for water-CuO nanofluids. Ebrahimi, et al. [101] evaluated nanofluid flow's with a rectangular MCHS with LVG, as exhibited in Fig. 7-b. The research signifies that water-Al_2O_3 nanofluids improve heat transfer by 2.29–30.63 % and water-CuO nanofluids by 9.44–53.06 %, but with a higher ΔP of 3.49–16.85 %. Tian, et al. [102] considered two semi-longitudinal, non-central triangular VGs, as presented in Fig. 7-c. The study determined that nanofluids increased the Nu and exergy destruction, improving the heat transfer by 11 % in the non-central VG configurations. Circular cross-sections exhibited a superior thermal performance. VGs, specifically those with nanofluids, boosted heat transfer, promising a heat exchanger design breakthrough of 20 % compared to a traditional channel without MHD, with the ideal GR having the lowest skin friction coefficient.

Kummitha, et al. [103] rearranged delta winglets used as VGs to improve plate-fin HE heat transfer, as described in Fig. 7-d. The study optimised heat exchanger performance by placing winglets and using nanofluid. Optimised winglet placement increased the Nu by 23.2 %, reduced the ΔP by 17.67 %, and generated ideal results with 3 % Al_2O_3. Al Muallim, et al. [104] investigated nanofluid with LVGs to strengthen MCHS performance, as shown in Fig. 7-e. It was revealed that the most efficient base fluid was CuO-Polyalphaolefin, with Nu between 9.57 and 15.88 and increases in the f of 0.022–0.096. The results indicate that all configurations of MCHS with LVGs and nanofluids have a COP greater than 1.

Bayat, et al. [23] studied the angles of attack and nanoparticles in VGs, as illustrated in Fig. 7-f. The study found that increasing the angle of attack improved flow mixing and heat diffusion. The Nu increased significantly at an angle of attack of 30°. At −90°, the f was at its greatest, while the higher concentrations of Al_2O_3 increased the velocity dissipation and f.

Feng, et al. [107] examined a MCHS with longitudinal and transverse VGs and Al_2O_3, as shown in Fig. 7-g. An exergy efficiency of 94.30 % and a COP of 22.34 % higher than smooth mini-channels was achieved via a triangular transverse VG. The best structure had a COP of 1.36 and exergy efficiency of 97.63 %, using a triangular transverse VG and a 90° longitudinal VG. Wang, et al. [108] compared pin fins and VGs in MCHS along with Al_2O_3 nanofluid and DI-water, as described in Fig. 7-h. Oval pin fins outperformed round and diamond pin fins in terms of the COP.

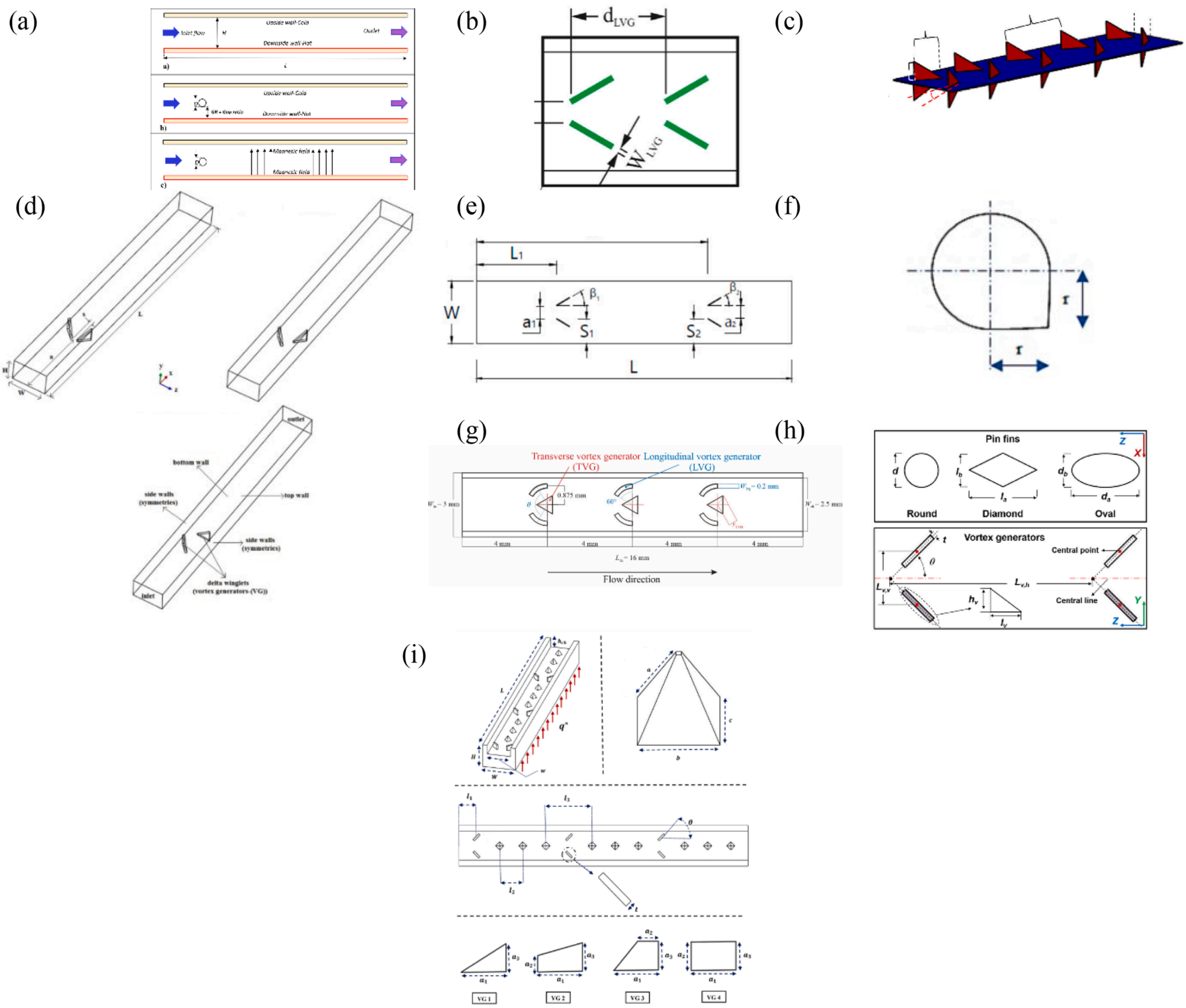

Fig. 7. Nanofluid with vortex generators: a)- Farrokhi Derakhshandeh and Gharbia [13], b)- Ebrahimi, et al. [101], c)- Tian, et al. [102], d)- Kummitha, et al. [103], e)- Al Muallim, et al. [104], f)- Bayat, et al. [23], g)- Feng, et al. [107], h)- Wang, et al. [108], i)- Torbatinejad, et al. [109].

Oval pin fins with 0.4 mm spacing and 0.1 mm height exhibited the highest COP. The optimal VG (0.08 mm length, 0.06 mm height) boosted the performance factor by 30 % compared to rectangular microchannels by way of improving the fluid mixing. Torbatinejad, et al. [109] investigated Al_2O_3/water nanofluid heat dissipation in a MCHS using varied nanoparticle morphologies and VGs, as exhibited in Fig. 7-i. It was observed that platelet-shaped nanoparticles demonstrate the most significant heat transfer, whereas rectangular VGs at 45° increase the Nu by 56 %. The Nu is 40 % higher with platelet-shaped nanoparticles than pure water (Table 1).

2.7. Applications of vortex generators in heat exchanger performance optimisation

This section explores recent studies that investigate the effects of different vortex generator geometries and placements on heat transfer and fluid flow behaviour in heat exchangers and microchannel systems. The studies include simulations and experimental analyses of VG-enhanced models, explaining their ability to improve the Nu, reduce ΔP, and optimise the COP. These developments in VG applications aid the design of more efficient and compact thermal management systems in a variety of industries, including aerospace, electronics cooling and energy systems [110–113].

Sun, et al. [4] simulated four basic models (CFD-I, CFD-V, CFU-I, CFU-V) and four enhanced models with elliptical cylinders throughout, as revealed in Fig. 8-a. The addition of elliptical cylinders increased the Nu by 8.4–14.1 % in CFD-I, 6.1–12.0 % in CFD-V, −1.9–5.0 % in CFU-I, and 11.0–14.9 % in CFU-V, with the COP ranging from 1.05 to 12.25, 1.00–1.13, 0.97–1.16 and 1. Compared to smooth channels, CFD-V and CFU-I with elliptical cylinders improved the Nu by 61 and 63 % and the COP by 25 and 22 %, respectively. Zhao, et al. [22] investigated compound angle film cooling for the protection of turbine engine components using VGs, pulsation, along with their interactions, as shown in Fig. 8-b. The study examines cooling efficiency and coolant separation at compound angles of 0°, 30° and 60°. Pulsation improves cooling performance at lateral angle of 0° by reducing the coolant separation, although this does not occur at 30° or 60°. Shi, et al. [10] examined the three-dimensional flow of a wavy elliptic cylinder and its wake at wavelengths, in relation to hydraulic diameter ratios of 3.43, 4.58 and 6.01, as depicted in Fig. 8-c. The shortest ratio of 3.43 illustrated a spiral motion from the node to the saddle point, with counter-rotating vortices and a wavy vortex structure. Higher ratios of 4.58 and 6.01 caused stable

Table 1
Nanofluid with vortex generators.

Authors	Nanofluid used	VG Shape	Key Findings
Farrokhi Derakhshandeh and Gharbia [13]	Al_2O_3	Cylindrical	Heat transfer improved by 20 % with optimised parameters.
Ebrahimi, et al. [101]	Al_2O_3, CuO	Rectangular	Water- Al_2O_3 improved heat transfer by 30.63 %, Water-CuO by 53.06 %.
Tian, et al. [102]	Al_2O_3, CuO	Triangular	Nanofluids increased the Nusselt number and reduced exergy damage.
Kummitha, et al. [103]	Al_2O_3	Delta Winglet	Optimised heat transfer with nanofluid and delta winglet VGs.
Al Muallim, et al. [104]	CuO	Longitudinal Vortex Generators	Most effective performance observed with CuO-Polyalphaolefin nanofluids.
Bayat, et al. [23]	Al_2O_3	Various angles of attack	Higher nanoparticle concentrations increased heat transfer and flow resistance.
Feng, et al. [107]	Al_2O_3	Longitudinal and Transverse Vortex Generators	Exergy efficiency attained 94.3 %, a significant improvement in COP.
Wang, et al. [108]	Al_2O_3	Pin fins with Vortex Generators	Oval pin fins and VGs notably improved thermal performance.
Torbatinejad, et al. [109]	Al_2O_3	Rectangular	Platelet-shaped nanoparticles exhibited the greatest thermal improvement.

recirculation and vortex shedding to bifurcate.

Zhao, et al. [110] investigated delta winglets and micro ramps for film cooling in high-performance turbine engines, as described in Fig. 8-d. The paper examined how these VGs generate an anticounter-rotating vortex pair (anti-CRVP) to improve coolant coverage and reduce lift-off during film cooling. Delta winglets produced less anti-CRVP than micro ramps. Combining upstream and downstream counter-rotating vortex pairs (CRVPs) reduce cooling performance without VGs. He, et al. [111] examined fin-and-tube HE with RWPVGs, as explained in Fig. 8-e. The research determined that RWPVGs generate longitudinal vortices that improve thermal mixing, delay boundary layer separation, and reduce the wake size behind the tubes. The common-flow-up orientation of RWPVGs creates a nozzle-like passage that accelerates flow and improves local heat transfer by directly impinging on downstream tubes. Saini, et al. [112] investigated a curved trapezoidal winglet VG with 0, 1, 2, 3 and 6 circulars, as observed in Fig. 8-f. The results confirmed that circular holes boosted heat transfer, with six holes increasing the Nu by 75.25 % and the ΔP by 107.88 and 125.51 %, respectively. Wu, et al. [113] explored how fin pitches and tube diameters affect air-side heat transfer in a tube bank fin HE with curved DWPVGs compared to plain fins, as exhibited in Fig. 8-g. Their study established that DWPVGs outperformed plain fins in heat transfer, with the largest fin pitch and smallest tube diameter delivering the most satisfactory performance. It was learnt that the Nu and f increased with fin pitch and that they were affected by the *Re* and tube diameter of the DWPVGs fins.

Qian, et al. [114] studied how RWPVGs improve heat transfer and flow resistance in fin-and-tube HE' weak regions behind the tubes, as presented in Fig. 8-h. They determined that the RWPVGs improve thermal performance and resistance. Furthermore, it was ascertained that the optimal geometry parameters were winglet length (3–5 mm), angle (30°–60°), and height (0.375–1.125 mm). In their research, Arora, et al. [115] studied a fin-and-tube HE with DWPVGs, as shown in Fig. 8-i. The study identified two optimal winglet locations in relation to HTE: one that maximises augmentation without considering flow loss and another that attains a balance between improvement and flow loss. The ideal locations are ($X = 0.1$D, $Z = \pm 0.9$D) for angles of attack between 15° and 30°, and ($X = 0.1$D, $Z = \pm 0.7$D) for angles between 45° and 60°. Dang, et al. [116] tested six fin patterns in a circular tube bank fin HE, including plane-RWPVG, curved-RWPVG, as well as curved trapezoidal vortex generators (CTVG), with and without flow redistributors (FRs), as observed in Fig. 8-j. The study determined that fins with both VGs and FRs outperform plain fins and those with only VGs. It was established that heat transfer increases with smaller fin spacing, whereas CRVG fins with FRs outperform curved-RWPVG and plane-RWPVG fins with FRs by 2.6 to 7.5 %. Chu, et al. [117] investigated LVGs in fin-and-oval-tube HE, as demonstrated in Fig. 8-k. The study ascertained that LVGs increased the ΔP by 29.2–40.6 % and the Nu by 13.6–32.9 %. The study also examined how LVG placement (upstream vs. downstream), angles of attack (15°, 30°, 45°, and 60°), and tube-row numbers (2–5) affected performance. The study confirmed that downstream LVGs with an angle of attack of 30° and fewer tube rows perform successfully in heat transfer. Al-Sumaily, et al. [118] investigated how thermal buoyancy affects the hydrodynamic and thermal properties of a horizontally heated cylinder in vertically upward laminar flow, as observed in Fig. 8-l. It was evidenced that at a moderate *Re*, the flow switched from unsteady vortex shedding to steady twin vortices as the Richardson number increased. This shift initially increased heat transfer, then reduced when critical Richardson numbers were achieved.

Tang, et al. [119] proposed an H-type finned elliptical tube HE with LVG, as shown in Fig. 8-m. Multi-objective optimisation revealed optimal parameters: length = 10 mm, height = 6 mm, angle = 24° and position = 19 mm, resulting in a 48–55 % improvement in performance. Brodnianská and Kotšmíd [120] determined that cylindrical VGs in wavy heated channels increased heat transfer, as exhibited in Fig. 8-n. The maximum COP was 0.8167 at 0.04 m channel height. It was confirmed that the wavy geometry and cylindrical VGs improved fluid mixing and heat transfer efficiency while reducing energy consumption. Lu and Zhai [121] studied fin-and-tube HE curved VGs, as shown in Fig. 8-o. It was determined that the COP was suitable for VGs with a curvature of 0.25, with the highest value of 1.06 at an angle of attack of 15°. Smaller VGs with greater inclination angles performed effectively at a lower *Re*, while larger ones delivered a more effective performance at a higher *Re*. Oh and Kim [122] calculated the thermal and fluid-flow characteristics of rectangular-winglet, delta-winglet-upstream (DWU), and DWD curved VGs, as demonstrated in Fig. 8-p. The study confirmed that placing CVGs at $\alpha = 30°$ created mixed vortices, improving heat transfer, while placing them behind the tube reduced the wake size and improved heat transfer.

Lu and Zhai [123] examined the thermal and flow properties of tear-drop delta VGs on fin-and-oval-tube HE fins surfaces, as revealed in Fig. 8-q. In a "common flow up" configuration, the VGs generated longitudinal vortices that reduced the wake region, improving heat transfer with a lower ΔP than plain fins. The study found that tear-drop delta VGs outperformed plane delta VGs at an optimal chord length ratio 2/3. Further analysis explained that the most effective COP was achieved with the following VG dimensions: a height 0.6 times the fin pitch, lateral length 0.3 times the fin pitch and a chord length 1.2–1.4 times the fin pitch. Liu, et al. [11] investigated how a delta airfoil can improve heat transfer in MCHS. Delta winglet VG (DWVG), delta airfoil VG (DAVG), and delta airfoil staggered VG (DASVG) channels with NACA0024 airfoil fins were employed, as observed in Fig. 8-r. Channels with VGs comprise a smaller local field synergy angle in comparison to non-VG channels, indicating excellent heat transfer. The DAVG configuration had the most effective COP, increasing the local heat transfer coefficient by 120 % in the pseudo-critical region.

Jayranaiwachira, et al. [124] examined HE tubes with louver-punched triangular baffle (LPTB) vortex generators in turbulent

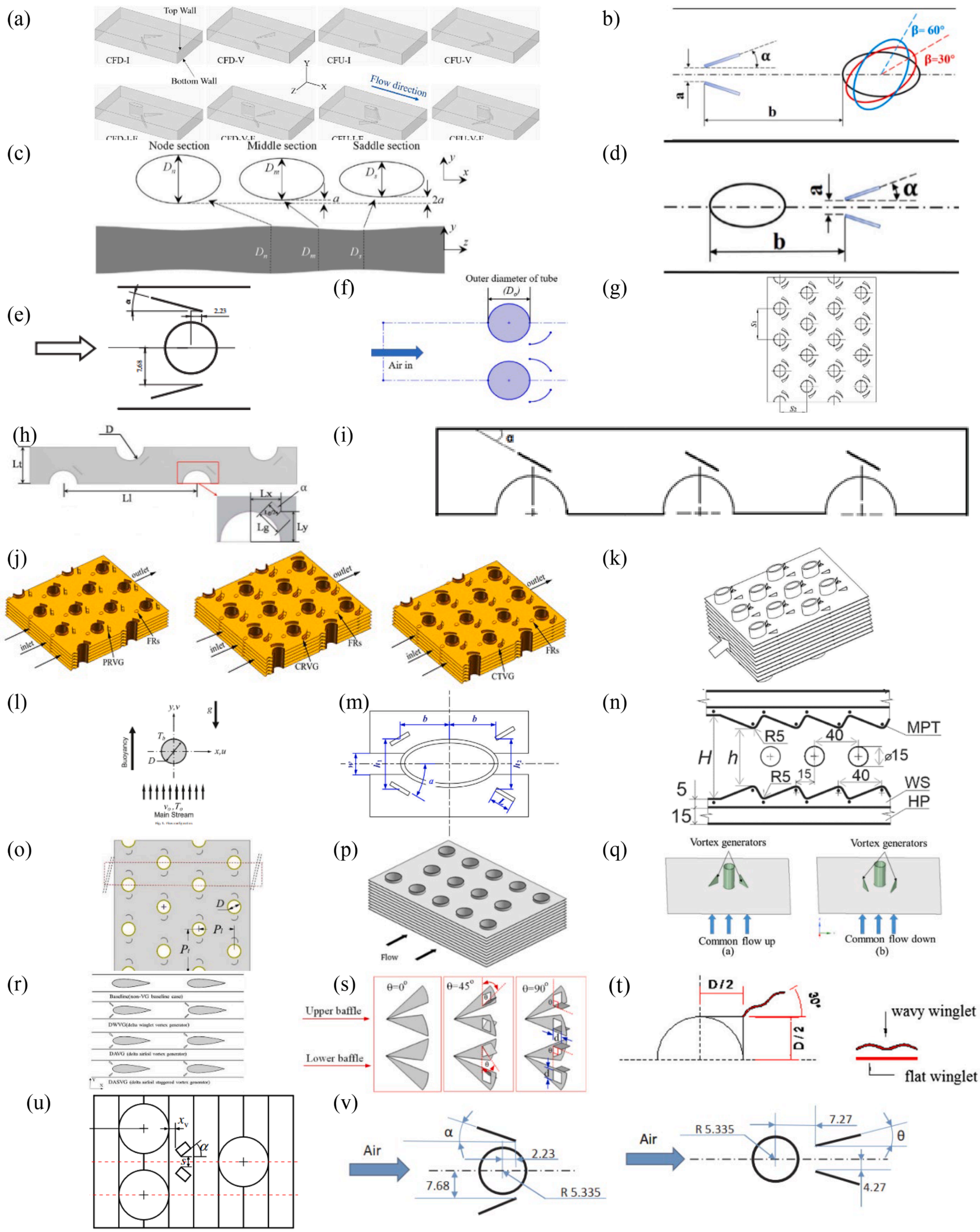

Fig. 8. Obstacles VGs: a)- Sun, et al. [4], b)- Zhao, et al. [22], c)- Shi, et al. [10], d)- Zhao, et al. [110], e)- He, et al. [111], f)- Saini, et al. [112], g)- Wu, et al. [113], h)- Qian, et al. [114], i)- Arora, et al. [115], j)- Dang, et al. [116], k)- Chu, et al. [117], l)- Al-Sumaily, et al. [118], m)- Tang, et al. [119], n)- Brodnianská and Kotšmíd [120], o)- Lu and Zhai [121], p)- Oh and Kim [122], q)- Lu and Zhai [123], r)- Liu, et al. [11], s)- Jayranaiwachira, et al. [124], t)- Gholami, et al. [125], u)- Gong, et al. [126], v)- Zeeshan, et al. [127].

flow, as illustrated in Fig. 8-s. One study ascertained that lowering the louver size ratio (LR) and angle (θ) improved the fluid mixing, giving rise to a higher Nu and f. The configuration with LR = 0 and θ = 0° produced the highest f (22.18 times) and Nu (5.1 times). The LPTB with LR = 0.24 and θ = 45° had the highest COP of 2.39 and 2.5 for baffle angles (α) of 30° and 45°, respectively. Gholami, et al. [125] investigated wavy RWVGs, as described in Fig. 8-t. Wavy RWVGs, conventional RWVGs and a baseline configuration without winglets were compared for heat transfer and flow structure. The results indicated that wavy RWVGs improve heat transfer with moderate ΔP. Gong, et al. [126] examined wavy fin-and-tube HE with combined RWVGs (CRWVGs), as shown in Fig. 8-u. Their studies determined that concerning the wavy fin punched with CRWPs, the Nu and f increased with an increase in the secondary angle of attack, accessory winglet length and accessory winglet width. In comparison with the wavy fin punched with RWPs, the Nu and f of the wavy fin punched with CRWP increased by 11.4–13.3 % and 21.4–26.9 %, respectively at β = 60°, c = 3 mm and d = 3 mm. Zeeshan, et al. [127] determined the optimal placement of rectangular winglet pairs (RWPs) in a fin-and-tube heat exchanger, as depicted in Fig. 8-v. The research they conducted identified that RWPs next to tubes increased heat transfer by 88.73–109.25 % at an angle of 25°, but increased the ΔP (39.05–65.19 %).

2.8. Applications of vortex generators in thermal performance enhancement

This section reviews key studies that investigate different vortex generator configurations and their applications in heat exchangers and MCHS. Each study provides beneficial information into how the use of wavy fins, electric field-induced vortices, flexible beams, along with

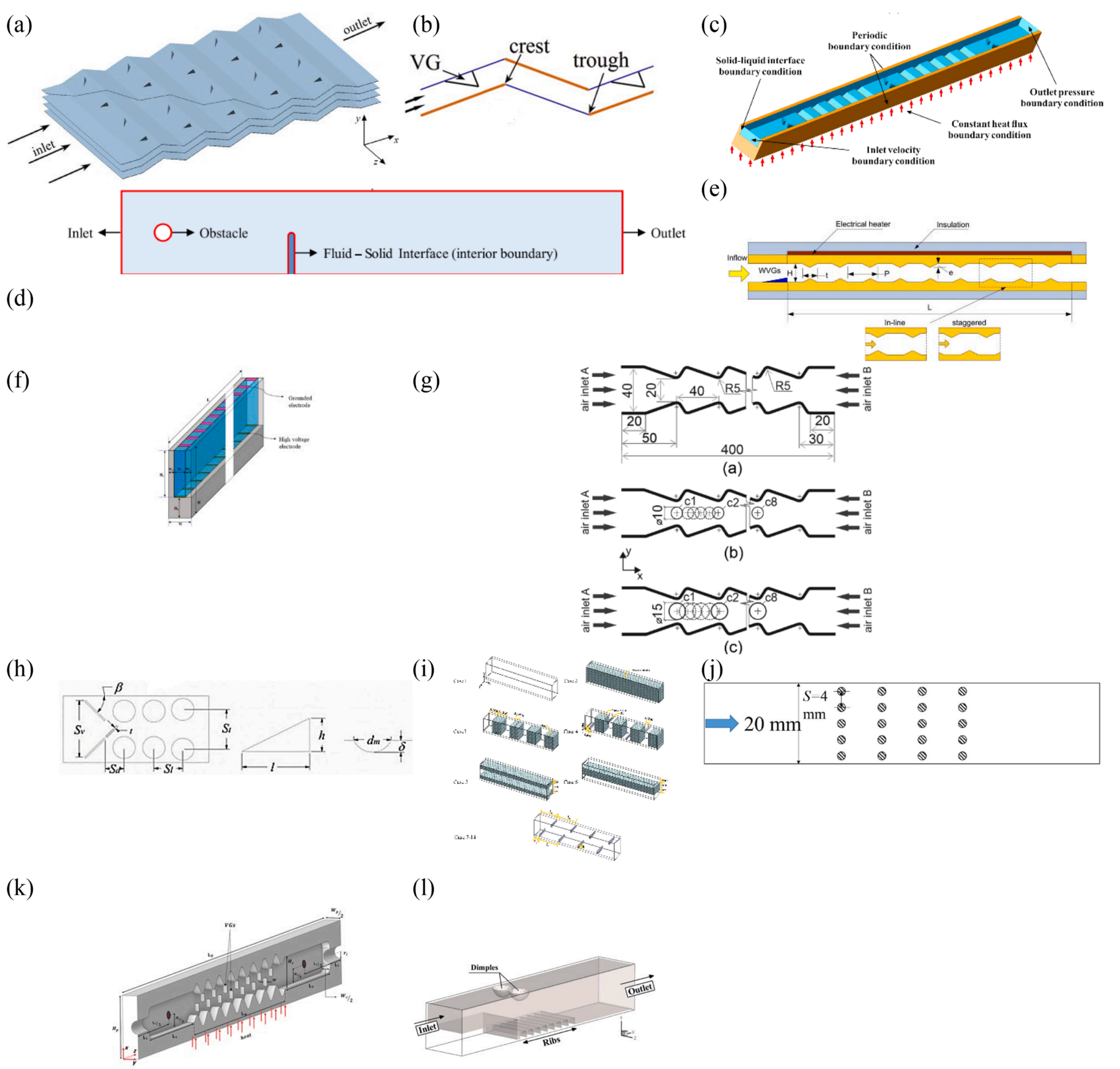

Fig. 9. Hybrid techniques with vortex generators: a)- Luo, et al. [128], b)- Luo, et al. [129], c)- Liu, et al. [20], d)- Dadvand, et al. [130], e)- Promvonge, et al. [131], f)- Vishnu, et al. [132], g)- Kotšmíd and Brodnianská [133], h)- Lu and Zhai [134], i)- Moosavi, et al. [135], j)- Xie and Zhang [136], k)- Salamatbakhsh and Bayer [137], l)- Yousefi, et al. [138].

cylindrical and winglet-type VGs can optimise heat transfer while balancing factors, such as ΔP and system efficiency. These developments illustrate the different ways in which VGs contribute to the development of more effective and energy-efficient thermal management solutions [128–130].

Luo, et al. [128] proposed a HE with VGs and wavy fins to improve thermal performance, as observed in Fig. 9-a. It was determined that heat transfer improves by 26.4 % when VGs with wavy fins are employed. Similarly, they showed that VGs perform ideally at 45° angles of attack.

Luo, et al. [129] investigated HE designs with wavy fins and VGs to boost thermal performance, as exhibited in Fig. 9-b. It was proven that longitudinal vortices increased on wavy fin crests and decreased on troughs. The most effective heat transfer performance was achieved with a VG angle of 60°, increasing the Nu by 31.5 % and f by 23.4 %, respectively. The maximum COP achieved was 1.23 at the optimal angle. Liu, et al. [20] established that the MC-LTC microchannel with LVGs and triangular cavities performed best thermally, as described in Fig. 9-c. The optimal pumping power was 0.706–1.018 mW, whilst the temperature uniformity factor was 0.547–0.716. Dadvand, et al. [130] examined a hybrid heat and mass transfer enhancement method using a rigid or flexible beam as a VG downstream of a cylindrical obstacle in a microchannel, as presented in Fig. 9-d. The study revealed that the oscillating flexible beam created periodic vortices that disrupted the thermal boundary layer, increasing heat transfer. Compared to the rigid beam case, the study determined a 18.46 % increase in the Nu, a reduction of 42.33 % in the f, a 42 % increase in the COP and an increase in the mixing index of 16.86 %.

Promvonge, et al. [131] studied the effects of ribs and winglet-type (WVGs), as portrayed in Fig. 9-e. The study examined in-line, staggered and WVGs at 60°, 45° and 30° angles of attack. Using ribs and WVGs together significantly improved heat transfer and the f. Larger angles of attack increased heat transfer and f, with in-line and WVG ribs showing the highest Nu and f, whilst staggered ribs demonstrated a greater thermal performance. Vishnu, et al. [132] used electric field-induced Onsager–Wien vortices to improve heat transfer in a rectangular MCHS, as described in Fig. 9-f. The study ascertained that heat transfer enhancement was proportional to the electric Re, attaining an increase of 48.25 % in the mean Nu with minimal power consumption of 20.7 mW. Kotšmíd and Brodnianská [133] examined cylindrical vortex generators (CVGs) with 10 mm and 15 mm outer diameters and five positions in a wavy channel, as exhibited in Fig. 9-g. Adding CVGs improved the Nu and Colburn factors in relation to each position and *Re*. CVGs in position 5, 15 mm diameter, backward air flow and $Re = 1677$ demonstrated the most efficient COP of 0.8229. Similarly, better fluid mixing in channel valleys made backward air flow more effective.

In the research they undertook, Lu and Zhai [134] combined VGs and dimples on a MCHS, as observed in Fig. 9-h. Compared to a smooth MCHS, VGs and dimples increased heat transfer by 23.4–59.8 % and f by 22.1–54.4 %, respectively. Additionally, the VG vortices were stronger than dimple vortices, increasing heat transfer. VGs in the "common flow down" performed better than the "common flow up". The most successful thermal hydraulic performance was achieved with a VG height ratio of 0.6, an angle of attack of $\beta = 45°$. Moosavi, et al. [135] considered TVGs and porous media in MCHS, as Fig. 9-i shows. The heat transfer coefficient increased significantly with TVG height and number. Fully filled porous media exhibited a 12-fold increase, whilst eight TVGs at a channel height of 12.5 % illustrated a 2.6-fold increase in comparison to an empty MCHS. Xie and Zhang [136] examined how dynamic VGs, specifically vibrating spherical cylinders, affect heat transfer and fluid flow, as described in Fig. 9-j. The results revealed that vibrating spherical cylinders improve convective heat transfer and velocity field distribution compared to stationary VGs. Vibration frequency improved the COP by 24.55 %. Salamatbakhsh and Bayer [137] researched the hydrothermal performance of a sinusoidal wavy MCHS with 14 VGs, as explained in Fig. 9-k. Three inline and three staggered wavy channel configurations with different VG angles of attack were evaluated. It was determined that the wavy channel with staggered VGs which tilted periodically at 45° comprised the highest COP of 1.4 to 1.46, compared to 1.17 to 1.36 for the channel without VGs. Yousefi, et al. [138] investigated how nanofluids and geometrical modifications affect backward-facing step MCHS, as Fig. 9-l shows. Their research proved that increasing the rib count from 4 to 8 improved the average Nu by 64.65 % at a higher *Re*. Likewise, increasing the rib height from 0.5H to 2H increased the Nu by 54.54 %.

2.9. *Optimisation of vortex generators using artificial intelligence and machine learning*

Advanced computer science approaches including Artificial Neural Networks and Response Surface Methodology have emerged as methods to improve the design of vortex generator. These methods present excellent solutions in relation to achieving the required characteristics of heat transfer coefficients and ΔP, specifically for complex geometries such as the MCHSs. The following are studies that have investigated enhancing VGs utilising AI/ML approaches [16–19].

Liang, et al. [16] optimised VG configurations in MCHSs to improve thermal performance and reduce ΔP, as explained in Fig. 10-a. It was determined that the ANN model generated more accurate predictions with optimal VG parameters including a 60° placement angle, 0.151 mm longitudinal distance and 0.166 mm transverse distance. Zhang, et al. [17] observed that common-flow-down winglet VGs surpassed continuous ribs in a high aspect ratio rectangular ribbed channel by 5.51 % in heat transfer. Similarly, it was established that the winglet VGs performed more satisfactorily than the tetrahedral VGs and delivered a superior thermal performance, as presented in Fig. 10-b. Wang, et al. [18] proposed modified RWVGs and a trapezoidal wing longitudinal (TWL), as shown in Fig. 10-c. Moreover, the novel combined winglet (NCW) generates stronger central vortices than the RWVGs. The accessory TWL creates a vortex and directs it into the tubes' wake, reducing the wake region and improving heat transfer on the bottom fin. Thus, the heat transfer improved by 1.8 to 24.2 %, whereas the ΔP increased from 1.3 to 29.1 %. Xie, et al. [19] optimised VGs in fin-tube HE, as illustrated in Fig. 10-d. Their experiment determined that ANN slightly outperformed the RSM in maximising the Nu and reducing the f. The optimal configurations for heat transfer, reduction in f and a balanced performance comprised an angle of attack of 160° and an arc angle of 10° with VG lengths of 8.345 mm using ANN and 13.545 mm using RSM.

3. Results

The analysis of recent studies on vortex generators underlines several significant findings related to heat transfer enhancement and reductions in ΔP. Throughout various studies, VGs consistently confirm their ability to improve the thermal performance of heat exchangers, microchannel heat sinks, and other cooling systems. The key findings are listed and shown in Fig. 11:

3.1. *VG shape and configuration*

- **Square Winglets, Rectangular Winglets and Trapezoidal VGs**: These shapes were identified to provide the best-shaped vortices, boosting fluid mixing and heat transfer, resulting in an improvement in the Nu of between 20 and 30 %.
- **Delta winglets:** These particular wings produced the maximum total heat transfer rates at each of the angles of attack due to their sharper leading edge, which creates a more effective vortex. This promoted an improvement in the Nu system of roughly 50–60 %. Nevertheless, they generated a greater ΔP with a rise of between 45 and 55 %.
- **Delta Winglets:** Heat transfer and ΔP: It was observed that in terms of each of the geometries under consideration, delta winglets provided the maximum heat transfer rates and enhanced Nu of

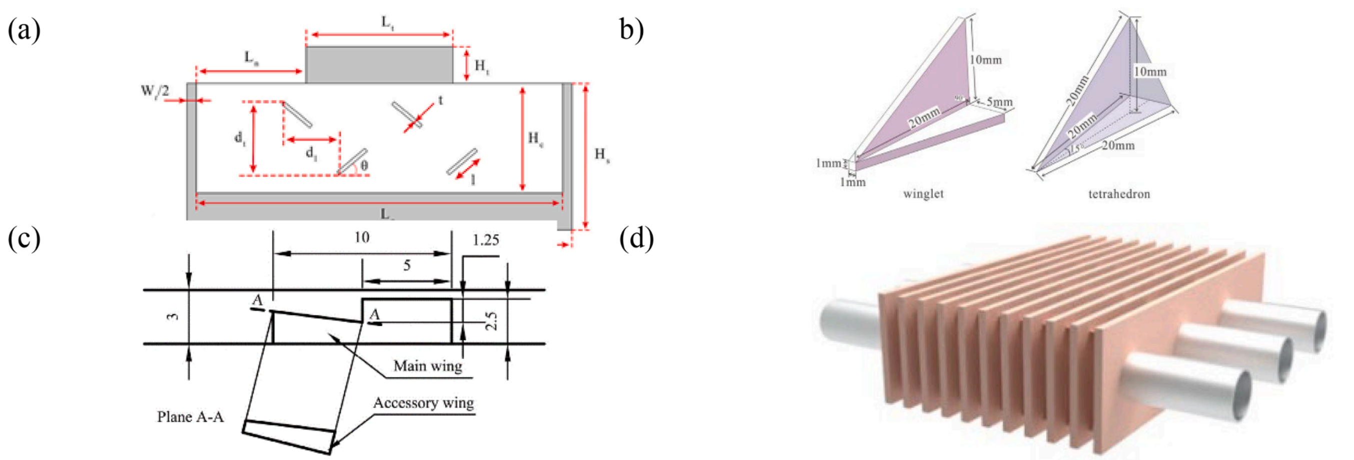

Fig. 10. Optimisation designs using Artificial Intelligence and Machine Learning: a)- Liang, et al. [16], b)- Zhang, et al. [17], c)- Wang, et al. [18], and d)- Xie, et al. [19].

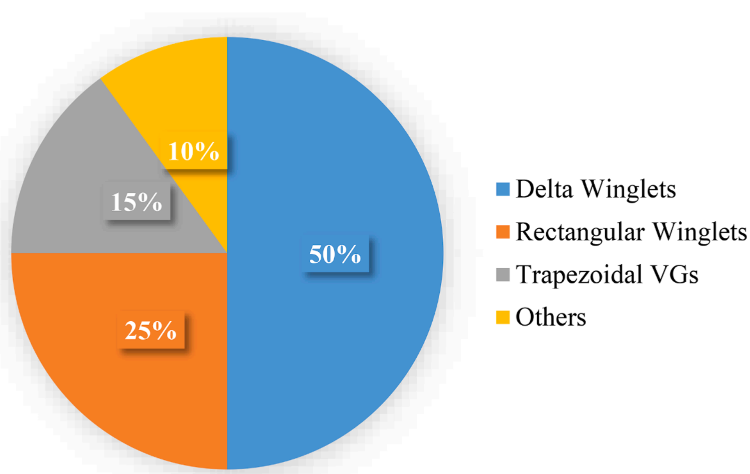

Fig. 11. Nu Improvement for VG shapes and Configurations.

approximately 50 to 60 %. Nevertheless, it was proved that the ΔP was 45 to 55 % higher than the other types.

- **Rectangular Winglets:** The rectangular winglets demonstrated a balanced increase in performance, which increased the Nu by 35–40 % and the ΔP by 25–30 %. Hence, they are suitable in conditions where convectional heat transfer and pressure loss are insignificant.
- **Trapezoidal vortex:** Generators exhibit a reasonable trade-off between heat transfer rates and ΔP as they augment the Nu by 30–40 % and ΔP by 30–35 %. Hence, they are suitable for cases where equality is desirable.
- **Rectangular Winglets:** These winglets achieved less tip span and produced a much improved thermal enhancement (Nu enhancement in the range of 35 to 40 %), in conjunction with a reasonable pressure penalty (ΔP ranging from 25 to 30 %). This suggests that they are more appropriate for systems that require both heat transfer and ΔP to be higher.
- **Trapezoidal VGs:** As discussed previously, although they have not been as extensively studied, they have exhibited methods to enhance performance in heat transfer by presenting a combination of an increase in heat transfer of between 30 and 40 % for the Nu and an increase in ΔP of between 30 and 35 %.

3.2. *Perforated vortex generators*

- The incorporation of perforations in the VGs resulted in a **25–35 %** improvement in heat transfer, while simultaneously reducing the ΔP by **50 %** compared to pin fins. The perforations boosted the through-flow area across the surface of the VG, giving rise to a lower ΔP while assisting with vortex generation, as illustrated in Fig. 12.

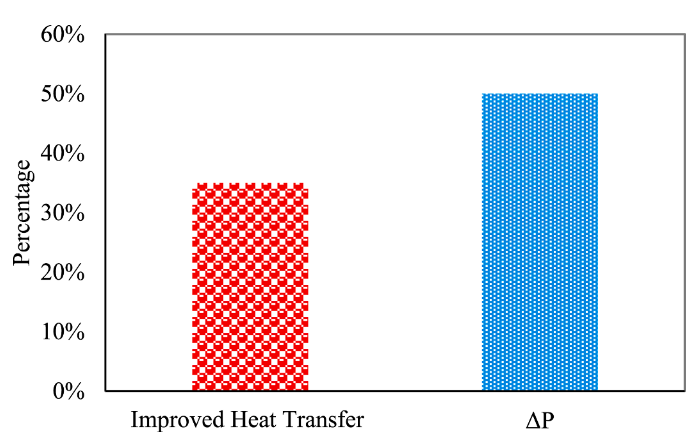

Fig. 12. HTE and a reduction in ΔP for perforated vortex generators.

3.3. Inclusion of nanofluids

- Nanofluid and VG Combination: Research entailing nanofluids and VGs revealed significant increases in thermal conductivity, bringing about improvements of between 30 and 40 % in the convective heat transfer coefficients. The inclusion of nanoparticles in the fluid increased heat transfer in the system, particularly when employed in combination with optimised VG designs.
- Nanofluid/VG System: The application of a combined nanofluid/VG system was considered to have the potential for even greater thermal effectiveness, with a 40–50 % improvement in heat transfer when both the heat transfer and ΔP parameters were optimised.
- Hybrid System: The hybrid approach of using nanofluids and VGs presents a promising opportunity to achieve greater thermal efficiency, particularly in applications where both high heat dissipation (50–60 % improvement) and a minimal ΔP (a reduction of up to 50 %) are essential, as illustrated in Fig. 13.

3.4. Pressure drop considerations

- Nanofluid and VG Combination: Research comprising nanofluids and VGs demonstrated significant increases in thermal conductivity, giving rise to improvements of between 30 and 40 % in the convective heat transfer coefficients. The addition of nanoparticles in the fluid increased heat transfer throughout the system, primarily when applied in combination with optimised VG designs.
- Nanofluid/VG System: The application of a combined nanofluid/VG system was believed to have the potential to produce even greater thermal effectiveness, with an improvement of between 40 and 50 % in heat transfer when both the heat transfer and ΔP parameters were optimised.
- Hybrid System: The hybrid approach of using nanofluids and VGs presents a promising way to obtain higher thermal efficiency, predominantly in applications where both high heat dissipation (improvement of 50–60 %) and a minimal ΔP (a reduction of up to 50 %) are vital, as explained in Fig. 14.

4. Future work

Notwithstanding that VGs have exhibited significant potential for heat transfer enhancement, there are several areas where further developments are required. The following research objectives are fundamental as regards the continued development and optimisation of VG technology:

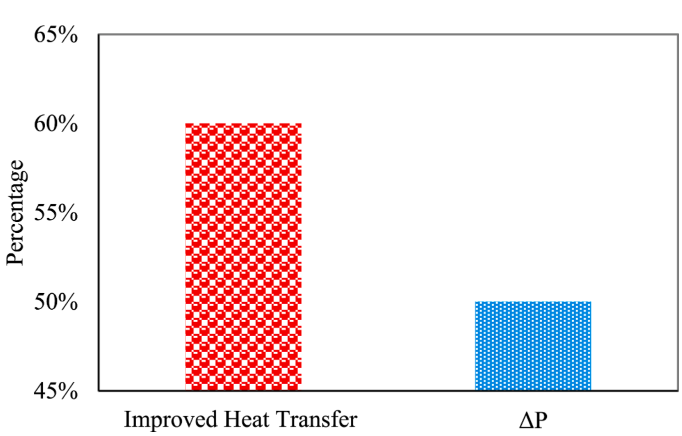

Fig. 13. HTE and ΔP reduction using nanofluids and VGs.

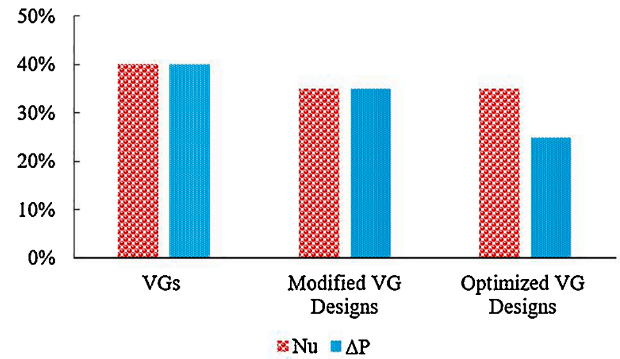

Fig. 14. HTE and ΔP reduction for VGs, Modified VG designs and Optimised VG.

4.1. Optimisation of VG geometries

- Modification of VG Shapes: Current research has essentially focused on conventional VG shapes, e.g., delta and rectangular. However, shapes such as trapezoidal and combination VGs remain under investigated. Preliminary studies propose that trapezoidal VGs can improve heat transfer efficiency by 10–15 % compared to rectangular designs, whilst maintaining acceptable ΔP levels. Further research should prioritise computational and experimental validation of these advanced geometries.
- Miniaturisation and Multi-Functionality: As applications continue to scale down, particularly in microchannel heat sinks, VGs must be optimised for small dimensions. Research into miniaturised, multi-functional VGs that combine heat transfer and ΔP control is crucial. Early Computational fluid dynamics (CFD) simulations indicate that micro-structured VGs could provide up to 20 % more efficiency in compact systems, which is imperative for electronics cooling and aerospace applications.
- Advanced Simulation Techniques: The integration of CFD simulations and machine learning algorithms is expected to accelerate the optimisation of VG configurations. Machine learning models can reduce optimisation times by up to 25 % by predicting the optimal VG shapes for different industrial applications, for instance in automotive radiators and industrial heat exchangers.

4.2. Material innovation

- High-Conductivity Materials: VGs made from graphene-based composites or carbon nanotubes could provide significant improvements in heat transfer efficiency, possibly increasing thermal conductivity by 5–10 % in comparison to traditional materials. Research should focus on developing materials that are lightweight but highly-conductive and capable of heightening the performance of VGs without adding excessive cost or weight, notably for aerospace and automotive applications.
- Smart and Phase-Change Materials (PCMs): Integrating smart materials or PCMs into VG designs could allow systems to adapt to varying thermal conditions. For example, PCMs can store and release heat, and in theory, improve the thermal management of VGs by up to 15 % under fluctuating thermal loads. Research into the compatibility of these materials with VGs is necessary to realise their full potential.

4.3. Integration with advanced fluids

- Nanofluids and Hybrid Fluids: Nanofluids, which have enhanced thermal conductivity, have exhibited promise in improving heat transfer when combined with VGs. However, long-term stability and practical application in industrial settings require further

experimental validation. Research should investigate new bio-based nanofluids that provide a similar performance with a reduced environmental impact. Additionally, the combination of nanofluids with phase-change nanofluids may deliver even greater efficiency, with potential heat transfer improvements of up to 40–50 %.
- Optimising VG Geometry for Nanofluid Performance: The interaction between nanofluids and VG geometry is not completely understood. Research should focus on how VG geometry influences fluid mixing and nanoparticle dispersion, with the aim of developing nanofluid performance without incurring excessive energy costs. Early studies indicate that non-spherical nanoparticles could improve fluid mixing by 20–30 % compared to spherical nanoparticles, which typically, could lead to a better system performance.

4.4. Microchannel and compact systems

- Scaling VGs for Microchannel Heat Sinks: The integration of VGs within microchannel heat sinks is an important area of focus in the present study. VG designs should be examined in relation to scaling given that they are incorporated into miniaturised systems. The preliminary CFD analysis indicates that by employing VGs, it is possible to boost heat transfer by 15–20 % in the case of MCHS. Future research should address how VG geometries scale down and how their performance is impacted by size and flow regimes in microchannels.
- Micro-Structured VGs for High-Performance Applications: It is crucial to continue designing micro-structured VGs that easily fit into high performing systems, for instance electronics cooling. Further studies should examine optimising designs to attain maximum heat transfer coefficients while decreasing the ΔP. The inclusion of micro-structured VGs, has the potential to increase cooling system efficiency by 20–30 %, specifically in high density electronic applications, in addition to aerospace cooling.

4.5. Environmental considerations and sustainability

- Lifecycle and Energy Efficiency: Research should use sensitive analysis to assess the energy saving and environmental impacts of incorporating VG-enhanced systems. Initial research claims that VG application can limit energy consumption by between 15 and 20 % in particular industrial uses. Nevertheless, further analysis should be conducted to evaluate the worldwide environmental cost of manufacturing, operating and maintaining VG systems.
- Sustainable VG Materials and Designs: Further research should investigate employing recycled materials in VG designs and cooling systems powered by solar which would minimise the use of non-renewable resources. VG technology can be easily incorporated into renewable energy systems making the cooling systems 25–30 % more environmentally friendly or ultimately, in low carbon schemes.

5. Conclusion

Vortex generators have demonstrated remarkable potential in furthering heat transfer efficiency in various applications, particularly in high-heat flux systems, for instance electronic cooling, heat exchangers and solar collectors. By generating secondary vortices and disrupting boundary layers, VGs develop convective heat transfer rates, with reported improvements in Nusselt numbers ranging from 10 to over 70 %, depending on VG configurations and operating conditions.

Different VG configurations, such as delta winglets, rectangular winglets, trapezoidal VGs, as well as perforated designs, aid thermal and hydraulic performance. For example, delta winglet VGs have been observed to increase heat transfer by 20 to 60 % compared to smooth channels, while trapezoidal VGs have exhibited improvements in COP of up to 1.7 %. Perforated VGs are particularly effective in reducing pressure losses by 10 to 25 %, while maintaining heat transfer rates that are comparable to their solid counterparts.

Geometrical parameters, such as the angle of attack, height and spacing considerably influence VG performance. Optimising these parameters has resulted in HTE as high as 73.8 %, with the added benefit of reducing the critical Re to below 2300, enabling efficient heat transfer even in laminar flow regimes. Nonetheless, this commonly results in an increase in the f, ranging from 40 to 150 %, depending on the specific VG design and system configuration. The primary challenge in determining the optimal balance between maximising thermal performance and minimising the ΔP remains, particularly in systems where pumping power is a serious constraint.

Hybrid approaches, combining VGs with other enhancement techniques, for example dimples or nanofluids, have further strengthened the effectiveness of VGs. Studies show that integrating perforated VGs with dimpled surfaces can increase heat transfer by 23 to 60 %, though the f also increases by 22 to 54 %. In combination with nanofluids, e.g., Al_2O_3 or CuO in water, HTE of up to 30.63 % have been observed, in conjunction with overall efficiency gains of between 9.78 and 50.64 %. These hybrid approaches provide more flexibility in managing both heat transfer and ΔP, making them suitable for high-performance cooling systems.

Optimisation techniques, such as Response Surface Methodology and Artificial Neural Networks, have become indispensable tools with regards to fine-tuning VG geometries. Multi-objective optimisation has led to heat transfer enhancements of 23.6 %, together with an gain in efficiency of 7.2 %, underlining the value of these methods in attaining an ideal balance between thermal and hydraulic performance.

The versatility of VGs is evident in a wide range of applications, from microchannel heat sinks to solar collectors and compact heat exchangers. For instance, in electronic cooling systems, VGs have reduced wall temperatures by up to 14.49 °C, while boosting heat transfer efficiency by 52 % at lower Re. These developments stress the potential of VGs to reduce thermal resistance and boost cooling performance in space-constrained environments.

Looking ahead, further miniaturisation of VGs for micro-scale applications demonstrates significant promise, particularly as the requirements for cooling in microelectronics continue to increase. The development of smaller, more efficient VGs will be crucial in maintaining high thermal performance in compact systems. Additionally, adaptive or flexible VGs, which dynamically respond to varying flow and thermal conditions, provide an exciting opportunity for real-time optimisation of cooling systems. These developments could bring about improvements of between 30 and 50 % in the entire system performance, while simultaneously reducing the energy consumption associated with fluid pumping.

In conclusion, VGs have made substantial advances in improving heat transfer efficiency and are ready to play an even greater role in future thermal management systems. Furthermore, by means of continuous innovation in design, materials and optimisation methods, VGs will continue to meet the changing needs of industries requiring high-performance cooling solutions.

CRediT authorship contribution statement

Mohammad Ismail: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdullah Masoud Ali:** Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Sol-Carolina Costa Pereira:** Writing – review & editing, Writing – original draft, Visualization, Resources.

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

The data that has been used is confidential.

References

[1] M. Ismail, Advanced bifurcation strategies in microchannel systems: a comprehensive review of heat transfer and flow optimisation techniques, Result. Eng. 24 (2024).
[2] M. Ismail, Experimental and numerical analysis of heat sink using various patterns of cylindrical pin-fins, Int. J. Thermofluid. (2024) 100737.
[3] M. Ismail, A. Manasrah, A.M. Ali, M. Abedalaziz, Hydrothermal performance of a heat sink using plate-fins: experimental and numerical investigations, Int. J. Thermofluid. 23 (2024) 100813.
[4] H. Sun, H. Fu, H. Ma, T. Sun, Y. Luan, P. Zunino, Heat transfer enhancement mechanism of elliptical cylinder for minichannels with delta winglet longitudinal vortex generators, Int. J. Therm. Sci. 198 (2024).
[5] Y. Wang, J. Yu, C. Qi, W. Zhang, L. Liang, Secondary vortex drag reduction and heat transfer enhancement of nanofluids in hierarchical microchannels applied to thermal management of electronic components, Appl. Therm. Eng. 236 (2024).
[6] A.M. Ali, A. Rona, H.T. Kadhim, M. Angelino, S. Gao, Thermo-hydraulic performance of a circular microchannel heat sink using swirl flow and nanofluid, Appl. Therm. Eng. 191 (2021).
[7] A.P. Mentzelopoulos, D. Fan, T.P. Sapsis, M.S. Triantafyllou, Variational autoencoders and transformers for multivariate time-series generative modeling and forecasting: applications to vortex-induced vibrations, Ocean Eng. 310 (2024).
[8] R. Vishnu, R.D. Selvakumar, S. Vengadesan, Effect of electrode configuration on minichannel heat sink with EHD vortex generators, Appl. Therm. Eng. 238 (2024).
[9] A.M. Ali, A. Rona, M. Angelino, Numerical investigation of various twisted tapes enhancing a circular microchannel heat sink performance, Int. J. Heat Fluid Flow 98 (2022) 109065.
[10] X. Shi, M. Mahbub Alam, H. Zhu, C. Ji, H. Bai, M. Sharifpur, Flow three-dimensionality of wavy elliptic cylinder: vortex shedding bifurcation, Ocean Eng. 301 (2024).
[11] X. Liu, Z. Zhao, C. Li, J. Ding, X. Pu, Investigation of local flow and heat transfer of supercritical LNG in airfoil channels with different vortex generators using field synergy principle, Appl. Therm. Eng. 242 (2024).
[12] J. Zhang, X. Hu, W. Li, J. Wang, L. Qi, J. Bi, Effects of airflow direction on the thermal-hydraulic performance of louvered fin-common flow up vortex generator, Case Stud. Therm. Eng. 59 (2024).
[13] F. Derakhshandeh, Javad, Y. Gharbia, The influence of magneto-hydrodynamics and vortex generators on nanofluids heat transfer, J. Magn. Magn. Mater. 597 (2024).
[14] A. Heydari, A. Noori, A. Khosravani Nezhad, K. Kord, Optimized heat transfer systems: exploring the synergy of micro pin-fins and micro vortex generators, Int. Commun. Heat Mass Transf. 153 (2024).
[15] G. Wu, J. Xu, H. Wang, W. Yin, Optimized design of multiple vortex generator rows to enhance thermo-hydraulic performance in fully developed forced convection channel, Int. Commun. Heat Mass Transf. 157 (2024).
[16] X. Liang, N.B. Kumar, I.B. Mansir, P.K. Singh, A.M. Abed, M. Dahari, S. Nasr, H. Albalawi, A. Cherif, M. Wae-hayee, Management of heat transfer and hydraulic characteristics of a micro-channel heat sink with various arrangements of rectangular vortex generators utilizing artificial neural network and response surface methodology, Case Stud. Therm. Eng. 44 (2023).
[17] G. Zhang, J. Liu, B. Sundén, G. Xie, Combined experimental and numerical studies on flow characteristic and heat transfer in ribbed channels with vortex generators of various types and arrangements, Int. J. Therm. Sci. 167 (2021).
[18] W. Wang, Y. Bao, Y. Wang, Numerical investigation of a finned-tube heat exchanger with novel longitudinal vortex generators, Appl. Therm. Eng. 86 (2015) 27–34.
[19] C. Xie, G. Yan, Q. Ma, Y. Elmasry, P. Kumar Singh, A.M. Algelany, M. Wae-hayee, Flow and heat transfer optimization of a fin-tube heat exchanger with vortex generators using Response Surface Methodology and Artificial Neural Network, Case Stud. Therm. Eng. 39 (2022).
[20] J. Liu, Z. Feng, Z. Li, S. Liang, J. Nie, Z. Wang, J. Zhang, F. Guo, D. Yuan, Temperature uniformity analysis and multi-objective optimization of the microchannel heat sink with cavities under longitudinal vortex flow, Int. J. Therm. Sci. 201 (2024).
[21] X. Wu, T. Fu, J. Wang, L. Zeng, F. Zhang, A comparative study of fluid flow and heat transfer in the tube with multi-V-winglets vortex generators, Appl. Therm. Eng. 236 (2024).
[22] Z. Zhao, F. Wen, Z. Li, C. Wan, X. Zhang, S. Wang, Effects of vortex generators and pulsation on compound angle film cooling, Appl. Therm. Eng. 244 (2024).
[23] M. Bayat, A. Basem, M. Sh Jaafar, M. Salah Dayoub, O. Ali Akbari, A. Marzban, F. Montazerifar, S. Salahshour, S. Baghaei, R. Sarlak, Entropy and energy analysis of water/silver nanofluid flow in a microchannel by changing the angle of attack of a cam-shaped vortex generator, Int. J. Thermofluid. 23 (2024).
[24] M.U.Z.P. Syaiful, B. Yunianto, N. Sinaga, Enhancing heat transfer in rectangular channels: an experimental study on perforated concave delta winglet vortex generators, Int. J. Heat Technol. 42 (1) (2024) 132–140.
[25] J. Wang, L. Zeng, T. Fu, S. Yu, Y. He, Effects of the position and perforation parameters of the delta winglet vortex generators on flow and heat transfer in minichannels, Int. J. Therm. Sci. 198 (2024).
[26] A. Gönül, A. Okbaz, N. Kayaci, A.S. Dalkilic, Flow optimization in a microchannel with vortex generators using genetic algorithm, Appl. Therm. Eng. 201 (2022).
[27] L.-T. Tian, Y.-L. He, Y.-G. Lei, W.-Q. Tao, Numerical study of fluid flow and heat transfer in a flat-plate channel with longitudinal vortex generators by applying field synergy principle analysis, Int. Commun. Heat Mass Transf. 36 (2) (2009) 111–120.
[28] M. Oneissi, C. Habchi, S. Russeil, D. Bougeard, T. Lemenand, Novel design of delta winglet pair vortex generator for heat transfer enhancement, Int. J. Therm. Sci. 109 (2016) 1–9.
[29] Y.-X. Li, X. Wang, J. Zhang, L. Zhang, J.-H. Wu, Comparison and analysis of the arrangement of delta winglet pair vortex generators in a half coiled jacket for heat transfer enhancement, Int. J. Heat Mass Transf. 129 (2019) 287–298.
[30] Y.L. He, H. Han, W.Q. Tao, Y.W. Zhang, Numerical study of heat-transfer enhancement by punched winglet-type vortex generator arrays in fin-and-tube heat exchangers, Int. J. Heat Mass Transf. 55 (21–22) (2012) 5449–5458.
[31] R.R. Moreno, A.M. Pérez, R.B. Pérez, Numerical optimization of a heat exchanger with slit fins and vortex generators using genetic algorithms, Int. J. Refriger. 119 (2020) 247–256.
[32] I. Yaningsih, A. Wijayanta, T. Miyazaki, S. Koyama, Impact of blockage ratio on thermal performance of delta-winglet vortex generators, Appl. Sci. 8 (2) (2018).
[33] K.W. Song, T. Tagawa, Z.H. Chen, Q. Zhang, Heat transfer characteristics of concave and convex curved vortex generators in the channel of plate heat exchanger under laminar flow, Int. J. Therm. Sci. 137 (2019) 215–228.
[34] S. Pourhedayat, S. Mehdi Pesteei, H. Ebrahimi Ghalinghie, M. Hashemian, M. A. Ashraf, Thermal-exergetic behavior of triangular vortex generators through the cylindrical tubes, Int. J. Heat Mass Transf. 151 (2020).
[35] Z. Li, Z. Feng, Q. Zhang, J. Zhou, J. Zhang, F. Guo, Thermal-hydraulic performance and multi-objective optimization using ANN and GA in microchannels with double delta-winglet vortex generators, Int. J. Therm. Sci. 193 (2023).
[36] H.N. Syaiful, M.S.K. Tony Suryo Utomo, A. Suprihanto, M.F. Soetanto, Numerical simulation of heat transfer enhancement from tubes surface to airflow using concave delta winglet vortex generators, Result. Eng. 16 (2022).
[37] J. Zhang, X. Hu, Y. Luo, Z. Hui, J. Wang, T. Yu, Effects of rectangular wing vortex generators on the thermal-hydraulic performance of louvered fin and flat tube heat exchanger, J. Therm. Sci. 32 (2) (2023) 628–642.
[38] A.H. Yousif, H.T. Kadhim, K.K.I. Al-Chlaihawi, 2D Numerical study of heat transfer enhancement using fish-tail locomotion vortex generators, Math. Modell. Eng. Probl. 8 (3) (2021) 386–392.
[39] J.M. Wu, W.Q. Tao, Effect of longitudinal vortex generator on heat transfer in rectangular channels, Appl. Therm. Eng. 37 (2012) 67–72.
[40] C. Chen, J.-T. Teng, C.-H. Cheng, S. Jin, S. Huang, C. Liu, M.-T. Lee, H.-H. Pan, R. Greif, A study on fluid flow and heat transfer in rectangular microchannels with various longitudinal vortex generators, Int. J. Heat Mass Transf. 69 (2014) 203–214.
[41] J.-F. Zhang, Y.K. Joshi, W.-Q. Tao, Single phase laminar flow and heat transfer characteristics of microgaps with longitudinal vortex generator array, Int. J. Heat Mass Transf. 111 (2017) 484–494.
[42] S. Jalali, E. Barati, M.F. Kalat, Numerical investigation of synergistic effects of magnetic fields and bluff bodies on heat transfer enhancement and pressure drop reduction in microchannels, Result. Eng. 24 (2024).
[43] A.Q. Ibrahim, R.S. Alturaihi, Experimental work for single-phase and two-phase flow in duct banks with vortex generators, Result. Eng. 15 (2022).
[44] A. Ebrahimi, E. Roohi, S. Kheradmand, Numerical study of liquid flow and heat transfer in rectangular microchannel with longitudinal vortex generators, Appl. Therm. Eng. 78 (2015) 576–583.
[45] A. Arora, P.M.V. Subbarao, Geometric parametrization of toe-out type vortex generators for energy-efficient capacity augmentation in finned-tube heat exchangers, Therm. Sci. Eng. Progr. 42 (2023).
[46] J. Zhao, B. Zhang, X. Fu, S. Yan, Numerical study on the influence of vortex generator arrangement on heat transfer enhancement of oil-cooled motor, Energies 14 (21) (2021).
[47] Y. Jiao, J. Wang, X. Liu, Heat transfer and flow characteristics in a rectangular channel with miniature cuboid vortex generators in various arrangement, Int. J. Therm. Sci. 153 (2020).
[48] M.T. Al-Asadi, F.S. Alkasmoul, M.C.T. Wilson, Benefits of spanwise gaps in cylindrical vortex generators for conjugate heat transfer enhancement in micro-channels, Appl. Therm. Eng. 130 (2018) 571–586.
[49] E. Hosseinirad, M. Khoshvaght-Aliabadi, F. Hormozi, Evaluation of heat transfer and pressure drop in a mini-channel using transverse rectangular vortex-generators with various non-uniform heights, Appl. Therm. Eng. 161 (2019).
[50] G. Lu, J. Yang, X. Zhai, X. Wang, Hotspot thermal management in microchannel heat sinks with vortex generators, Int. J. Therm. Sci. 161 (2021).
[51] Z. Lu, M. Li, C. Yang, X. Cheng, J. Zhang, Experimental and numerical study on the heat transfer and flow characteristics of micro-gap chip with longitudinal vortex generator array, Case Stud. Therm. Eng. 45 (2023).
[52] D. Yu, J.-L. Lin, J.-H. Xie, Investigation on the influence of vortex generator on particle resuspension, Particuology 86 (2024) 126–136.
[53] W. Jiansheng, J. Yu, L. Xueling, Heat transfer and flow characteristics in a rectangular channel with small scale vortex generators, Int. J. Heat Mass Transf. 138 (2019) 208–225.

[54] Y. Amini, S.E. Habibi, Effects of multiple flexible vortex generators on the hydrothermal characteristics of a rectangular channel, Int. J. Therm. Sci. 175 (2022).
[55] S.G. Park, Heat transfer enhancement by a wall-mounted flexible vortex generator with an inclination angle, Int. J. Heat Mass Transf. 148 (2020).
[56] R. Gallegos, B. Kristoffer, R.N. Sharma, Heat transfer performance of flag vortex generators in rectangular channels, Int. J. Therm. Sci. 137 (2019) 26–44.
[57] J.-F. Zhang, L. Jia, W.-W. Yang, J. Taler, P. Oclon, Numerical analysis and parametric optimization on flow and heat transfer of a microchannel with longitudinal vortex generators, Int. J. Therm. Sci. 141 (2019) 211–221.
[58] S. Zheng, Z. Feng, Q. Lin, Z. Hu, Y. Lan, F. Guo, K. Huang, F. Yu, Numerical investigation on thermal–hydraulic characteristics in a mini-channel with trapezoidal cross-section longitudinal vortex generators, Appl. Therm. Eng. 205 (2022).
[59] H. Karkaba, T. Dbouk, C. Habchi, S. Russeil, T. Lemenand, D. Bougeard, Multi objective optimization of vortex generators for heat transfer enhancement using large design space exploration, Chem. Eng. Process. - Process Intensifi. 154 (2020).
[60] A.K. Das, S.S. Hiremath, Investigation on the thermohydraulic performance and entropy-generation of novel butterfly-wing vortex generator in a rectangular microchannel, Therm. Sci. Eng. Progr. 36 (2022).
[61] M. Syaiful, M.S.K. Pranita Hendraswari, S.U. Tony, M.F. Soetanto, Heat transfer enhancement inside rectangular channel by means of vortex generated by perforated concave rectangular winglets, Fluids 6 (1) (2021).
[62] B. Lotfi, B. Sundén, Q. Wang, An investigation of the thermo-hydraulic performance of the smooth wavy fin-and-elliptical tube heat exchangers utilizing new type vortex generators, Appl. Energy 162 (2016) 1282–1302.
[63] A.K. Das, S.S. Hiremath, Multi-objective optimization of a novel butterfly-wing vortex generator fabricated in a rectangular microchannel based on CFD and NSGA-II genetic algorithm, Appl. Therm. Eng. 234 (2023).
[64] J. Wang, Y. He, L. Zeng, Z. Liu, C. Li, J. Dou, Thermohydraulic performance intensification in a rectangular channel using punched vortex generators, Int. Commun. Heat Mass Transf. 157 (2024).
[65] S. Skullong, P. Promthaisong, P. Promvonge, C. Thianpong, M. Pimsarn, Thermal performance in solar air heater with perforated-winglet-type vortex generator, Solar Energy 170 (2018) 1101–1117.
[66] J. Ma, Y.P. Huang, J. Huang, Y.L. Wang, Q.W. Wang, Experimental investigations on single-phase heat transfer enhancement with longitudinal vortices in narrow rectangular channel, Nucl. Eng. Des. 240 (1) (2010) 92–102.
[67] P. Saini, A. Dhar, S. Powar, Performance enhancement of fin and tube heat exchanger employing curved delta winglet vortex generator with circular punched holes, Int. J. Thermofluid. 20 (2023).
[68] A.J. Modi, N.A. Kalel, M.K. Rathod, Thermal performance augmentation of fin-and-tube heat exchanger using rectangular winglet vortex generators having circular punched holes, Int. J. Heat Mass Transf. 158 (2020).
[69] C. Habchi, T. Lemenand, D.D. Valle, H. Peerhossaini, Heat transfer in circular pipe fitted with perforated trapezoidal vortex generators, Heat Transf. Eng. 43 (14) (2021) 1179–1192.
[70] O. Heriyani, M. Djaeni, Syaiful, A.K. Putri, Perforated concave rectangular winglet pair vortex generators enhance the heat transfer of air flowing through heated tubes inside a channel, Result. Eng. 16 (2022).
[71] T.W. Syaiful, B. Yunianto, N. Sinaga, Evaluation of vortex generators in the heat transfer improvement of airflow through an In-line heated tube arrangement, Fluids 6 (10) (2021).
[72] M.T. Al-Asadi, F.S. Alkasmoul, M.C.T. Wilson, Heat transfer enhancement in a micro-channel cooling system using cylindrical vortex generators, Int. Commun. Heat Mass Transf. 74 (2016) 40–47.
[73] A.P. Sudheer, U. Madanan, Numerical investigation into heat transfer augmentation in a square minichannel heat sink using butterfly inserts, Therm. Sci. Eng. Progr. 36 (2022).
[74] I. Aguirre, A. González, E. Castillo, Numerical study on the use of shear-thinning nanofluids in a micro pin-fin heat sink including vortex generators and changes in pin shapes, J. Taiwan Instit. Chem. Eng. 136 (2022).
[75] F.A.S. da Silva, D.J. Dezan, A.V. Pantaleão, L.O. Salviano, Longitudinal vortex generator applied to heat transfer enhancement of a flat plate solar water heater, Appl. Therm. Eng. 158 (2019).
[76] J.S. Yang, M. Jeong, Y.G. Park, M.Y. Ha, Numerical study on the flow and heat transfer characteristics in a dimple cooling channel with a wedge-shaped vortex generator, Int. J. Heat Mass Transf. 136 (2019) 1064–1078.
[77] H. Karkaba, S. Russeil, J.V. Simo Tala, D. Bougeard, J. Boonaert, L. Etienne, U. Pelay, S. Lecoeuche, Effect of using multiple vortex generator rows on heat transfer enhancement inside an asymmetrically heated rectangular channel, Appl. Therm. Eng. 227 (2023).
[78] L. Luo, F. Wen, L. Wang, B. Sundén, S. Wang, On the solar receiver thermal enhancement by using the dimple combined with delta winglet vortex generator, Appl. Therm. Eng. 111 (2017) 586–598.
[79] J. Wang, Y. Zhao, Heat and fluid flow characteristics of a rectangular channel with a small diameter circular cylinder as vortex generator, Int. J. Therm. Sci. 92 (2015) 1–13.
[80] J. Wu, P. Liu, M. Yu, Z. Liu, W. Liu, Thermo-hydraulic performance and exergy analysis of a fin-and-tube heat exchanger with sinusoidal wavy winglet type vortex generators, Int. J. Therm. Sci. 172 (2022).
[81] M. Dogan, S. Erzincan, Experimental investigation of thermal performance of novel type vortex generator in rectangular channel, Int. Commun. Heat Mass Transf. 144 (2023).
[82] L.H. Tang, W.X. Chu, N. Ahmed, M. Zeng, A new configuration of winglet longitudinal vortex generator to enhance heat transfer in a rectangular channel, Appl. Therm. Eng. 104 (2016) 74–84.
[83] A.J. Modi, M.K. Rathod, Experimental investigation of heat transfer enhancement and pressure drop of fin-and-circular tube heat exchangers with modified rectangular winglet vortex generator, Int. J. Heat Mass Transf. 189 (2022).
[84] M.J. Hasan, K. Tawkir, A.A. Bhuiyan, Improvement of an exhaust gas recirculation cooler using discrete ribbed and perforated louvered strip vortex generator, Int. J. Thermofluid. 13 (2022).
[85] M.K. Fahad, N.F. Ifraj, S.H. Tahsin, M.J. Hasan, Numerical investigation of the hydrothermal performance of novel vortex generators in a rectangular channel by employing inclination and rotational angles, Int. J. Thermofluid. 20 (2023).
[86] A.J. Modi, M.K. Rathod, Comparative study of heat transfer enhancement and pressure drop for fin-and-circular tube compact heat exchangers with sinusoidal wavy and elliptical curved rectangular winglet vortex generator, Int. J. Heat Mass Transf. 141 (2019) 310–326.
[87] J. Yang, Y. Zhang, H. Chen, S. Fu, Flow separation control in a conical diffuser with a Karman-vortex generator, Aerosp. Sci. Technol. 106 (2020).
[88] M.T. Al-Asadi, A. Al-damook, M.C.T. Wilson, Assessment of vortex generator shapes and pin fin perforations for enhancing water-based heat sink performance, Int. Commun. Heat Mass Transf. 91 (2018) 1–10.
[89] M.F.B. Raihan, M.T. Al-Asadi, H.M. Thompson, Management of conjugate heat transfer using various arrangements of cylindrical vortex generators in micro-channels, Appl. Therm. Eng. 182 (2021).
[90] H. Linardos, G. Mavrogenis, D. Margaris, Novel designs of LVGs conformations and introduction of Batch Heated and Channeled pipe for increasing heat transfer efficiency in pipes, Result. Eng. 13 (2022).
[91] J. Lu, D. Zhuang, Y. Wang, G. Ding, Effects of vortex generator on subcooled flow boiling characteristics in micro-channel, Int. J. Heat Mass Transf. 216 (2023).
[92] S.A. Isaev, M.S. Gritckevich, A.I. Leontiev, O.O. Milman, D.V. Nikushchenko, NT Vortex enhancement of heat transfer and flow in the narrow channel with a dense packing of inclined one-row oval-trench dimples, Int. J. Heat Mass Transf. 145 (2019).
[93] Z. Zhao, L. Luo, D. Qiu, X. Zhou, Z. Wang, B. Sundén, Experimental evaluation of longitudinal and transverse vortex generators on the endwall of a serpentine passage, Int. J. Therm. Sci. 176 (2022).
[94] Z. Feng, C. Zhou, F. Guo, J. Zhang, Q. Zhang, Z. Li, The effects of staggered triangular ribs induced vortex flow on hydrothermal behavior and entropy generation in microchannel heat sink, Int. J. Therm. Sci. 191 (2023).
[95] Y. Chen, Z. Liu, D. He, Numerical study on enhanced heat transfer and flow characteristics of supercritical methane in a square mini-channel with dimple array, Int. J. Heat Mass Transf. 158 (2020).
[96] Z. Feng, P. Jiang, S. Zheng, Q. Zhang, Z. Chen, F. Guo, J. Zhang, Experimental and numerical investigations on the effects of insertion-type longitudinal vortex generators on flow and heat transfer characteristics in square minichannels, Energy 278 (2023).
[97] L. Du, J. Yuan, Y. Qu, N. Deng, Z. Zhang, W. Hu, H. Wang, Numerical analysis of fluid flow and heat transfer characteristics in single crystal diamond microchannels with ribs and secondary channels, Chem. Eng. Sci. 300 (2024).
[98] T. Lemenand, C. Habchi, D.D. Valle, H. Peerhossaini, Vorticity and convective heat transfer downstream of a vortex generator, Int. J. Therm. Sci. 125 (2018) 342–349.
[99] C. Liu, J.-tong Teng, J.-C. Chu, Y.-lang Chiu, S. Huang, S. Jin, T. Dang, R. Greif, H.-H. Pan, Experimental investigations on liquid flow and heat transfer in rectangular microchannel with longitudinal vortex generators, Int. J. Heat Mass Transf. 54 (13–14) (2011) 3069–3080.
[100] A.M. Ali, M. Angelino, A. Rona, Numerical analysis on the thermal performance of microchannel heat sinks with Al2O3 nanofluid and various fins, Appl. Therm. Eng. 198 (2021) 117458.
[101] A. Ebrahimi, F. Rikhtegar, A. Sabaghan, E. Roohi, Heat transfer and entropy generation in a microchannel with longitudinal vortex generators using nanofluids, Energy 101 (2016) 190–201.
[102] M.-W. Tian, S. Khorasani, H. Moria, S. Pourhedayat, H.S. Dizaji, Profit and efficiency boost of triangular vortex-generators by novel techniques, Int. J. Heat Mass Transf. 156 (2020).
[103] O.R. Kummitha, S.K.R. Dwarshala, K. Chary, V. Mangam, H. Chirala, N. M. Battina, Effect of vortex generator placement and nanofluids on channel flow heat transfer, Heat Transf. Eng. (2023) 1–15.
[104] B. Al Muallim, M.A. Wahid, H.A. Mohammed, M. Kamil, D. Habibi, Thermal–hydraulic performance in a microchannel heat sink equipped with longitudinal vortex generators (LVGs) and nanofluid, Processes 8 (2) (2020).
[105] A.M. Ali, M. Angelino, A. Rona, Physically consistent implementation of the mixture model for modelling nanofluid conjugate heat transfer in minichannel heat sinks, Appl. Sci. 12 (14) (2022) 7011.
[106] A.M. Ali, A. Rona, A. Bagdanavicius, Guidance on using two-phase models for predicting the performance of a nanofluid minichannel heat sink, Powder Technol. 452 (2025) 120531.
[107] Z. Feng, Q. Zhang, S. Liang, Z. Li, F. Guo, J. Zhang, D. Yuan, Hydrothermal, entropy generation and exergy performances analysis in a mini-channel with combination of longitudinal and transverse vortex generators using Al2O3 nanofluids, Powder Technol. 432 (2024).
[108] J. Wang, K. Yu, M. Ye, E. Wang, W. Wang, B. Sundén, Effects of pin fins and vortex generators on thermal performance in a microchannel with Al2O3 nanofluids, Energy 239 (2022).

[109] A. Torbatinejad, M.J. Hosseini, Y. Pahamli, Enhancement of heat dissipation in a minichannel by different structural designs of vortex generators and aluminum oxide hydroxide nanoparticles, Int. J. Heat Fluid Flow 107 (2024).

[110] Z. Zhao, F. Wen, X. Tang, J. Song, Y. Luo, Z. Wang, Large eddy simulation of film cooling with vortex generators between two consecutive cooling rows, Int. J. Heat Mass Transf. 182 (2022).

[111] Y.-L. He, P. Chu, W.-Q. Tao, Y.-W. Zhang, T. Xie, Analysis of heat transfer and pressure drop for fin-and-tube heat exchangers with rectangular winglet-type vortex generators, Appl. Therm. Eng. 61 (2) (2013) 770–783.

[112] P. Saini, A. Dhar, S. Powar, Performance enhancement of fin and tube heat exchanger employing curved trapezoidal winglet vortex generator with circular punched holes, Int. J. Heat Mass Transf. 209 (2023).

[113] X. Wu, Z.-M. Lin, S. Liu, M. Su, L.-C. Wang, L.-B. Wang, Experimental study on the effects of fin pitches and tube diameters on the heat transfer and fluid flow characteristics of a fin punched with curved delta-winglet vortex generators, Appl. Therm. Eng. 119 (2017) 560–572.

[114] Z. Qian, Q. Wang, J. Cheng, Analysis of heat and resistance performance of plate fin-and-tube heat exchanger with rectangle-winglet vortex generator, Int. J. Heat Mass Transf. 124 (2018) 1198–1211.

[115] A. Arora, P.M.V. Subbarao, R.S. Agarwal, Development of parametric space for the vortex generator location for improving thermal compactness of an existing inline fin and tube heat exchanger, Appl. Therm. Eng. 98 (2016) 727–742.

[116] W. Dang, J. Nugud, Z.-M. Lin, Y.-H. Zhang, S. Liu, L.-B. Wang, The performances of circular tube bank fin heat exchangers with fins punched with quadrilateral vortex generators and flow re-distributors, Appl. Therm. Eng. 134 (2018) 437–449.

[117] P. Chu, Y.L. He, Y.G. Lei, L.T. Tian, R. Li, Three-dimensional numerical study on fin-and-oval-tube heat exchanger with longitudinal vortex generators, Appl. Therm. Eng. 29 (5–6) (2009) 859–876.

[118] G.F. Al-Sumaily, H.A. Dhahad, H.M. Hussen, M.C. Thompson, Influence of thermal buoyancy on vortex shedding behind a circular cylinder in parallel flow, Int. J. Therm. Sci. 156 (2020).

[119] S.-Z. Tang, F.-L. Wang, Y.-L. He, Y. Yu, Z.-X. Tong, Parametric optimization of H-type finned tube with longitudinal vortex generators by response surface model and genetic algorithm, Appl. Energy 239 (2019) 908–918.

[120] Z. Brodnianská, S. Kotšmíd, Heat transfer enhancement in the novel wavy shaped heat exchanger channel with cylindrical vortex generators, Appl. Therm. Eng. 220 (2023).

[121] G. Lu, X. Zhai, Effects of curved vortex generators on the air-side performance of fin-and-tube heat exchangers, Int. J. Therm. Sci. 136 (2019) 509–518.

[122] Y. Oh, K. Kim, Effects of position and geometry of curved vortex generators on fin-tube heat-exchanger performance characteristics, Appl. Therm. Eng. 189 (2021).

[123] G. Lu, X. Zhai, Analysis on heat transfer and pressure drop of fin-and-oval-tube heat exchangers with tear-drop delta vortex generators, Int. J. Heat Mass Transf. 127 (2018) 1054–1063.

[124] N. Jayranaiwachira, P. Promvonge, Pitak Promthaisong, Mahdi Erfanian Nakhchi, and Sompol Skullong, heat transfer analysis in a tube contained with louver-punched triangular baffles, Result. Eng. 22 (2024).

[125] A.A. Gholami, M.A. Wahid, H.A. Mohammed, Heat transfer enhancement and pressure drop for fin-and-tube compact heat exchangers with wavy rectangular winglet-type vortex generators, Int. Commun. Heat Mass Transf. 54 (2014) 132–140.

[126] J. Gong, C. Min, C. Qi, E. Wang, L. Tian, Numerical simulation of flow and heat transfer characteristics in wavy fin-and-tube heat exchanger with combined longitudinal vortex generators, Int. Commun. Heat Mass Transf. 43 (2013) 53–56.

[127] M. Zeeshan, S. Nath, D. Bhanja, A. Das, Numerical investigation for the optimal placements of rectangular vortex generators for improved thermal performance of fin-and-tube heat exchangers, Appl. Therm. Eng. 136 (2018) 589–601.

[128] C. Luo, S. Wu, K. Song, L. Hua, L. Wang, Thermo-hydraulic performance optimization of wavy fin heat exchanger by combining delta winglet vortex generators, Appl. Therm. Eng. 163 (2019).

[129] C. Luo, K. Song, T. Tagawa, X. Wu, L. Wang, Thermal performance of a zig-zag channel formed by two wavy fins mounted with vortex generators, Int. J. Therm. Sci. 153 (2020).

[130] A. Dadvand, S. Hosseini, S. Aghebatandish, B.C. Khoo, Enhancement of heat and mass transfer in a microchannel via passive oscillation of a flexible vortex generator, Chem. Eng. Sci. 207 (2019) 556–580.

[131] P. Promvonge, T. Chompookham, S. Kwankaomeng, C. Thianpong, Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators, Energy Convers. Manage. 51 (6) (2010) 1242–1249.

[132] R. Vishnu, R.D. Selvakumar, A.K. Alkaabi, S. Vengadesan, Active vortex generation and enhanced heat transfer in a 3D minichannel by Onsager–Wien effect, Appl. Therm. Eng. 233 (2023).

[133] S. Kotšmíd, Z. Brodnianská, The effect of diameter and position of transverse cylindrical vortex generators on heat transfer improvement in a wavy channel, Mathematics 10 (23) (2022).

[134] G. Lu, X. Zhai, Analysis on heat transfer and pressure drop of a microchannel heat sink with dimples and vortex generators, Int. J. Therm. Sci. 145 (2019).

[135] R. Moosavi, M. Banihashemi, C.-X. Lin, P.-Y.A. Chuang, Combined effects of a microchannel with porous media and transverse vortex generators (TVG) on convective heat transfer performance, Int. J. Therm. Sci. 166 (2021).

[136] P. Xie, X. Zhang, The influence of active dynamic control flow vortexes on enhancing convective heat transfer, Int. J. Therm. Sci. 168 (2021).

[137] E. Salamatbakhsh, Ö. Bayer, Hydrothermal performance of a wavy minichannel heatsink with longitudinal vortex generators, Therm. Sci. Eng. Progr. 50 (2024).

[138] S. Yousefi, M. Mahdavi, S.S.M. Ajarostaghi, M. Sharifpur, Hydrothermal behavior of nanofluid flow in a microscale backward-facing step equipped with dimples and ribs; Lattice Boltzmann method approach, Therm. Sci. Eng. Progr. 43 (2023).