A Comprehensive Review of Methods for Improving Single-Phase Heat Transfer in Heat Exchanger Applications

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Abstract: *The purpose of this work is to evaluate the various methods that have been employed to increase the rate of heat transfer in heat exchanger devices, such as solar air heaters, turbine cooling blades, and so on, using single phase heat transfer fluids. Recent publications' findings regarding the advancement of new technologies like Magnetohydrodynamics (MHD) and Electrohydrodynamics (EHD) are also covered. Several strategies can be used to improve heat transfer in heat exchangers. These methods fall into two categories: active and passive. While the passive methods use surface modification, either on a heated surface or by inserting swirl devices in the flow field, the active methods require some external power. In motion although these techniques have a lot of potential and can be controlled thermally, they are quite complicated due to the external power source. Passive techniques include winglets, expanded surfaces, artificial roughness, and the addition of swirl devices, which change the flow pattern and disrupt the thermal boundary layer, leading to increased heat transfer. Since passive techniques are simple to implement in already-existing heat exchangers, they are more common than active techniques. This paper reviews the different heat transfer mechanisms used in heat exchangers and attempts to classify the active and passive approaches. Significant outcomes have been enumerated for easy access. It has been determined that only active or passive approaches have been used. A mixed approach that incorporates both active and passive strategies has also been suggested based on the literature.*

Keywords: *Heat exchanger, Heat transfer enhancement, Swirl device, Electrohydrodynamics (EHD), Vortex generators, Magnetohydrodynamics (MHD)*

I. Introduction

Due to the rise in population, industrialisation, and urbanisation over the past ten years, energy consumption has skyrocketed. As a result, researchers have been working to create new energy sources and energy-saving techniques. Fossil fuels including coal, oil, natural gas, nuclear, etc. are traditionally used to generate energy. The environment is negatively impacted by these fuels, which are naturally exhaustible. Despite this, scientists have worked to reduce the environmental impact of these fossil fuel emissions. CO2 emissions from power plants [1–3] and NOX emissions from diesel engines [4, 5] have been limited or minimised in the environment.

Additionally, small and effective thermal systems are being created to reduce energy use. One of the most practical thermal systems, heat exchangers are utilised in commercial, industrial, and residential settings. Heat exchangers can be found in the refrigeration, power plant cooling, automobile radiators, chemical processing, solar air/water heaters, waste heat recovery, cogeneration, steam generation, and pharmaceutical sectors. Enhancing the heat transfer rate can improve the heat exchanger's performance, which in turn affects thermal control, energy efficiency, and material savings.
A variety of strategies that improved convective heat transfer by lowering thermal resistance at the heated surface were developed in response to the need for high heat transfer in heat exchangers.

Enhanced heat transfer rates typically result in higher pressure drops, which raises the need for pumping power. Scientists have been working to create methods that increase the velocity of heat transmission while minimising the pressure drop.These methods involve forcing fluids including water, air, ethylene glycol, mineral oil, and other nanofluids onto a heated surface. Depending on the use, the heated surface might be stationary, rough, smooth, or moving. Active and passive methods are the two main categories into which heat transfer improvement techniques fall. To increase the rate of heat transfer in the active approach, some external power input is required. Depending on the needs of the system, the external power can be applied to fluids or heated surfaces. Because external effects make it difficult to analyse flow structure, active approaches are complex. Passive approaches often use changed surfaces and/or the insertion of elements (turbulence promoters) in the flow and do not require any external power. By changing the flow treatment, this technique raises the convective heat transfer coefficient. By generating turbulence in the flow, turbulence promoters aid in the removal of the thermal boundary layer and encourage fluid mixing, which accelerates the rate of heat transfer.

Artificial roughness [6,7], ribs [8,9], baffles [10,11], rib-groove [12,13], blocks [14,15], fins [16–18], and impediments are some examples of many turbulence promoters. Investigations have been conducted into [19–21], turbulators [22,23], and the usage of swirl devices like cans [24], conical rings [25,26], coiled wires [27,28], twisted tapes [25,29], vortex rings [30,31], and winglets [32,33]. An attempt has been made in this work to provide a summary of the several approaches that deal with the use of both active and passive methods in heat exchangers. The key findings have been highlighted in order to arrive at the suggested approach.

II. An Overview on Active and Passive Techniques

As was previously said, in order to enhance heat transfer, the active approach needs an external energy source. Certain thermal systems can have their operational life and functionality impacted by operating at extremely high temperatures or being subjected to severe heat. deterioration and failure of the system before its designated lifespan may pose a risk to safety. Reliability, performance, and lifespan are guaranteed by cooling system components by eliminating surplus heat from hot spots and/or by using or rejecting heat sinks. It can be somewhat challenging to control the system's external energy source under certain situations. The ability to regulate flow modification according to system requirements is one of these technologies' advantages; for example, ferrofluid is best controlled by a magnetic field. Additional instances of active techniques include the deployment of an electric field, pulsing flow, and vibrating heat transfer surfaces. Active approach demands additional work to research and build a heat exchanger that is both compact and efficient.

The passive approach increases fluid turbulence by drawing a tiny amount of energy from the system itself, but it doesn't need an external energy source to improve heat transmission. Because to its straightforward design, limited scope, and dependability, this approach is highly favoured in several industries. Increased flow turbulence and a high heat transfer rate are the results of surface alteration and/or turbulator insertion. This technique can also be used to improve heat transfer by employing fins or other extended heat surfaces to expand the heat transfer area. Fins are employed to increase turbulence in the flow field in addition to expanding the area for heat transfer. Increased heat transmission is accomplished at the expense of a pressure decrease, which manifests as pumping power from a fan or pump. Small height ribs typically reduce the amount of power needed for pumping since they don't interfere with the main flow, and flow separation and reattachment only affect the thermal boundary layer, increasing the heat transfer coefficient. The passive approach simply increases the pumping power requirement by using energy from the system itself, negating the need for an external energy source.

III. Active Method

In order to increase the rate of convective heat transfer, active methods require additional power, as was previously mentioned. The restricted practical application of active approaches restricts their use and the challenge of an external power source in many situations. In Fig. 1, active techniques are grouped according to the external power source.

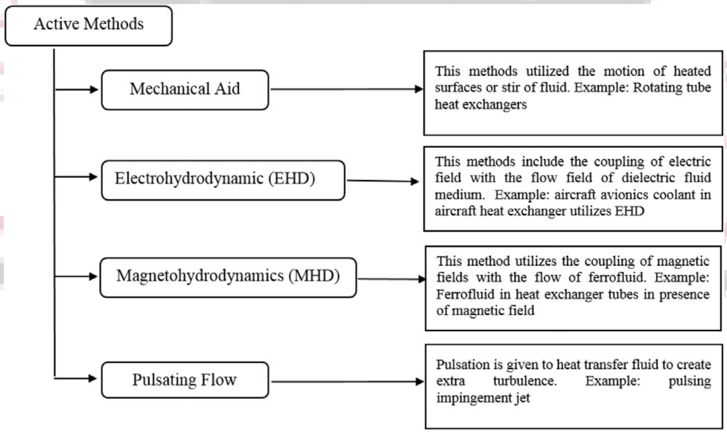

Figure 1: Active methods based on external power supply

III-A Mechanical Aid

The thermal boundary layer at the heated surface needs to be breached in order to speed up heat transmission, which can be done by stirring or moving the fluid with some mechanical force. The most popular method in this category is rotating the heat transfer wall with the use of mechanical power, which increases the rate of heat transfer by creating turbulence in the flow. Morris and Rahmat-Abadi [34] conducted an experimental investigation of convective heat transport in a spinning circular pipe with internal ribs. The tube was rotated in orthogonal mode, and three distinct rib geometries were examined. Secondary flow was discovered to improve heat transmission on the tube's trailing edge. The cariolis force caused the secondary flow. The rectangular duct in rotating mode was examined by Wright et al. [35]. Six distinct rib types are present in the duct: angled, discrete angled, V-shaped, discrete V-shaped, W-shaped, and discrete W-shaped ribs. The rib characteristics that were taken into consideration were the rib pitch to height ratio (p/e) of 10 and the rib height to hydraulic diameter ratio (e/D) of 0.078. Despite their high stated friction factor, discrete V-shaped and discrete W-shaped ribs were found to perform better in both rotating and non-rotating duct modes.

The experimental study conducted by Li et al. [36] was based on the enhancement of heat transmission in a rotating U-turn smooth channel. Uneven (d = 24.5 mm) and rectangular (d = 19.6 mm) shapes were employed for the inlet and exit passes, respectively. For the inlet and exit passes, the rotation number ranges were 0–0.72 and 0–0.37, respectively. The findings showed that, under rotating and stationary conditions, the highest improvement in the Nusselt number on the trailing edge relative to the leading edge was 4.3 and 1.5, respectively. The effect of rotating a smooth square duct in a U shape on pressure drop and heat transmission was experimentally examined by Qui et al. [37]. Rotation was found to have a more significant impact on the increase in Nusselt number, particularly in the turn region. As rotation increased, the Nusselt number ratio rose linearly; nevertheless, the friction factor fluctuated in tandem with the rotation number. The heat transmission in a wedge-shaped channel in rotation mode with lateral fluid extraction was experimentally examined by Tao et al. [38].

Additionally, the impact of five distinct channel orientations and two distinct outlet boundary conditions has been examined. The findings showed that channel orientation had an impact on the rotation effect on the flow and heat characteristics. Rotation number critical values were discovered to be approximately 0.3. The impact of a spinning cylinder on heat transfer properties under a lateral air impingement jet was examined by Jeng et al. [39]. By maintaining the cylinder's height and diameter constant, the relative jet-impingement distance (L/w) and the cylinder diameter to nozzle width (D/w) were adjusted from 1 to 16 and 2 to 16, respectively. According to reports, there was a critical value for the relative jet-impingement distance (L/w) that produced the maximum Nusselt number. Although this technique significantly increases heat transfer, the heated surface's motion also causes an undesired high pressure penalty. The summary of significant studies with mechanical assistance is provided in Table I for easy access.

Table I: Summary of important investigations using mechanical aid.

S. No.	Authors	Study description	Key results
1	Wright et al. [35]	Effect of ribs in rotating rectangular duct.	Both rotating and non-rotating mode of duct provided better thermal performancein case of discrete V and W ribs
2	Qui et al. [37]	Effect of rotating smooth square duct in U-shape.	Significant enhancement in Nusselt number mainly in the turn region.
3	Tao et al. [38]	Investigation of heat transfer in wedge shape channel in rotation mode with lateral fluid extraction.	Leading to trailing averaged Nusselt number ratio was decreased with decreasing rotation speed
4	Jeng et al. [39]	Effect of lateral air impingement jet in rotating cylinder	Increment in average Nusselt number was reported with the values of jet Reynolds number (Rej) and the rotational Reynolds number (Rer),

III-B Electrohydrodynamic (EHD)

EHD techniques removed the heated surface's mobility because they make advantage of the electric field's effect on the heat transfer fluid, which might be a dielectric fluid that reacts to an electric field. The application of high voltage and low current to a fluid is what defines an electric field. Interaction between the dielectric fluid and the electric field transforms applied electric energy in the form of an electric field into fluid kinetic energy. By increasing the fluid's velocity in a radial direction and disrupting the boundary layer, the heat transfer was improved. An experimental investigation of electrically charged particles in turbulent flow pipes was carried out by Yoshida et al. [40]. Experiments covered the following ranges: 0–6 kV, 0–0.6, and 5200–12,000 for applied potential, loading ratios, and Reynolds number. The values of the Nusselt number grew as the loading ratio and applied potential increased; the greatest augmentation in Nusselt was reported to be 1.8 times greater than that without an electric field. Kui [41] examined the impact of an electric field on heat transmission in a heat exchanger's heat pipe.

As variables of Reynolds number, provided voltage, and its nature, correlations between temperature efficiency, heat transfer rate, and heat transfer coefficient were established. The performance of a thermosyphon heat exchanger caused by air in both the presence and absence of electrohydrodynamics at very low Reynolds numbers was investigated by Wangnippartno et al. [42]. A 15% improvement in heat transfer was observed at a provided voltage of 17.5 kV, a 58% Reynolds number, and a 10% enhancement at a Reynolds number of 230.

Tada et al. [43] examined the electric field-controlled heat transfer properties in gas-solid solution. Fig. 2 displays the experimental setup. Air-borne hollow particles moved between the plate and parallel electrode that surrounded the channel. It was discovered that particles carrying heat over the thermal boundary layer and frequently colliding with channel walls boosted heat transfer. Additionally, simulations were run, and the numerical findings showed good agreement with the experimental data. The summary of significant EHD-based experiments is provided in Table II for easy access.

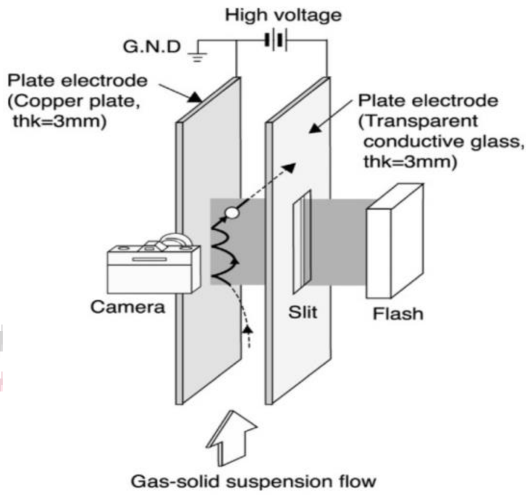

Figure 2: Experimental setup by Tada et al. [43]

Table II: Summary of important investigations using EHD.

S. No.	Authors	Study description	Key results
1	Yoshida et al. [41]	Study of heat transfer enhancement due to motion of electrically charged solid particles	The greatest boost in Nusselt was observed to be 1.8 times more than that without an electric field, and it increased with the loading ratio and applied voltage.
2	Wangnippartno et al. [43]	Performance of thermosyphon heat exchanger due to fluid (air) in the absence and the presence of electrohydrodynamic	Considerable improvement in heat transfer was reported when applied voltage more than 15.5 kV and heat transfer was improved in range of 0.5–20%.
3	Tada et al. [43]	Effect of gas-solid suspension, controlled by electric field	Heat transfer was increased due to heat transport by electric charged from hot region to colder region.

III-C Magnetohydrodynamics (MHD)

The enhancement of heat transmission of ferrofluid (Fe3O4 nanoparticle) in the heated copper tube was examined by Lajvardi et al. [44]. Various ferrofluid concentrations (= 2.5% and 5% by vol.) and magnetic field intensities (0, 800, 1000, and 1200 G) were taken into consideration. The results showed that the rate of heat transfer increased as concentrations and magnetic fields increased because high thermal conductivity was attributed to a greater ferrofluid concentration (5% vol.) in the presence of a high magnetic field (1200 G). Using a water-based magnetite fluid and a magnetic field, Motozawa et al. [45] investigated heat transmission in a rectangular smooth duct, as illustrated in Fig. 3.

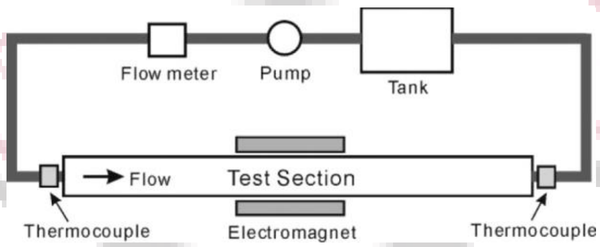

Figure 3: Schematic diagram of experimental setup [45]

Convective heat transfer and pressure decrease in a heat exchanger tube were examined by Azizian et al. [46]. The effects of magnetic field gradient, strength, homogeneity, number of magnets, and arrangement on heat transfer properties were investigated using nine different magnet configurations. The findings showed that the presence of a magnetic field quadrupled local heat transmission, with Reynolds number, magnetic field gradient, and strength all having an impact.

The effects of various magnetic fields were also examined in addition to the continuous magnetic field. The convective heat transfer of ferrofluid via a heated circular copper tube while subjected to an alternating magnetic field was examined by Ghofrani et al. [47]. The ferrofluid concentrations used in the experiments ranged from 0% to 2% (by vol.). With a maximum magnetic field of 0.02 T, the alternating magnetic field frequencies of 5 Hz and 50 Hz were taken into consideration. It was shown that low Reynolds number (Re = 80) and high frequency magnetic field (f = 50 Hz) enhanced maximal convective heat transfer by 27.6%. Table III presents the summery of important investigations using MHD.

Table III: Summary of important investigations using MHD.

S. No.	Authors	Study description	Key results
1	Lajvardi et al. [44]	Effect of concentration of ferrofluid under magnetic field	Heat transfer was increased with increase in concentration and magnetic field
2	Motozawa et al. [45]	Effect of magnetite fluid under the influence of magnetic field	Heat transfer increased locally in those regions where magnetic field exist
3	Azizian et al. [46]	Effect of magnets configuration, magnetic field gradient, strength, uniformity and number of magnets	Local heat transfer was improved with increasing the magnetic field strength and gradient.
4	Ghofrani et al. [47]	Effect of alternating magnetic field on ferrofluid passing in heated circular copper tube	Significant heat transfer was obtained for high concentration under high frequency of magnetic field

III-D Pulsating flow

This approach is comparable to mechanical assistance. Heat transfer fluid is subjected to pulse or oscillating motion in order to disrupt or shatter the thermal barrier layer through flow instability and turbulence. Heat transmission was improved as a result of alternate expansion and shrinkage, which assisted in exchanging vortexes with the main stream. This approach made use of a single-phase flow. The pulsing flow has been the subject of numerous studies, some of which are covered below.

The impact of pulsing flow in a triangular grooved channel was examined by Jin et al. [48] (Fig. 4). Heat transmission was enhanced by the vigorous mixing induced by the pulsing flow and the repeating process of vortex production and mixing with the main stream. According to reports, pulsating flow enhanced the rate of heat transfer by 350% as compared to constant flow.

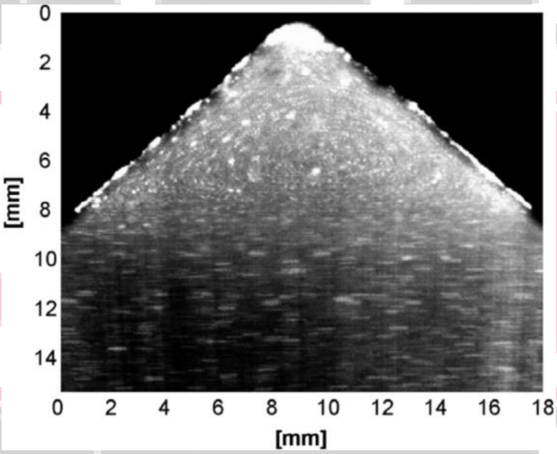

Figure 4: Flow visualization of pulsating flow [48]

Jafari et al. [49] employed pulsing flow in a corrugated channel to study convective heat transfer. Water was mixed with nanoparticles of single-walled carbon nanotubes (SWCNTs). The impact of the pulsing flow's frequency (0.05–0.25) and amplitude (0–0.5) were taken into account. It was determined that, in the case of pure fluid as opposed to SWCNT nanofluid, pulsing flow improved heat transmission. Heat transmission in a 2D wavy microchannel was also numerically examined by Nandi and Chattopadhyay [50]. To investigate the thermal behaviour, various oscillation frequency (1–10) and amplitude (0.2–0.8) ranges were taken into consideration. The performance parameter improved as a result of improved heat transfer and decreased pressure drop. Seliefendigil and Oztop [51] conducted a numerical investigation on the fluid flow and heat transfer characteristics caused by a pulsing rectangular jet. Summary of important investigations pulsating flow have been presented in Table IV.

Table IV: Summary of important investigations using Pulsating flow.

S. No.	Authors	Study description	Key results
1	Jin et al. [48]	Effect of pulsating flow in triangular grooved channel	Repeating sequence of vortex generation and its mixing with the main stream lead to improved convective heat transfer rate. Heat transfer rate was increased by 350%.
2	Jafari et al. [49]	Effect of pulsating flow in corrugated channel	Pulsating flow helped in heat transfer enhancement in case of pure fluid rather than SWCNT nanofluid
3	Nandi and Chattopadhyay [50]	Heat transfer investigation of sinusoidal flow condition of fluid in a 2D wavy micro channel.	Enhancement in heat transfer and reduction in pressure drop were achieved by introducing pulsation in the flow.
4	Selimefendigil and Oztop [51]	Effect of volume fraction of nanoparticles and pulsating frequency	Nusselt number was increased with increase in nano particle concentration and Reynolds number. Heat transfer was increased by 18.8%

IV Passive Method

As was previously mentioned, no outside energy is needed for this technique to improve heat transfer. To generate turbulence in the flow field, this technique makes use of extended or modified surfaces. The flow's turbulence serves to change the flow pattern, which breaks the thermal boundary layer. Although this approach does not require external power, these strategies increased the pumping power requirements, which come from the pump/blower. The extended/modified surfaces have been used to group various passive approaches, as seen in Fig. 4.

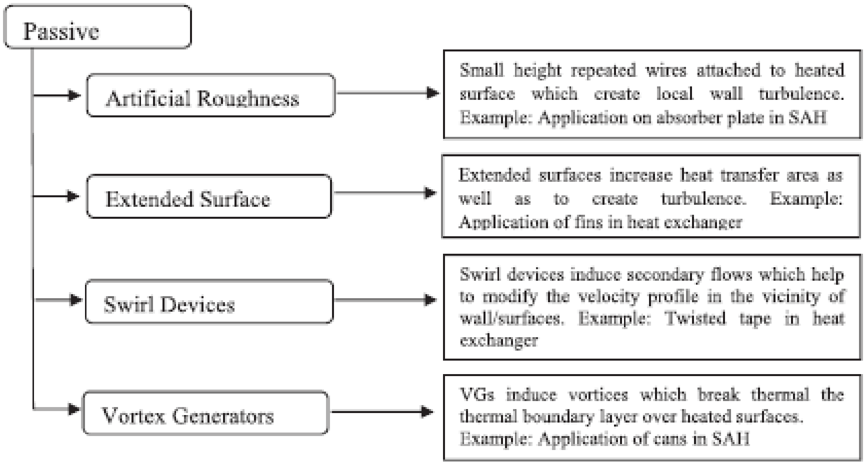

Figure 4: Classification of passive methods based surface modifications/turbulence promoters.

IV-A Artificial roughness

Artificial roughness is one of the most widely employed turbulence promoters in solar air heaters. Small height repeating ribs are used to produce artificial roughness on the absorber plate's bottom. Because the flow separates and reattaches between successive ribs, artificial roughness interrupts the laminar sub-layer and produces local wall turbulence without interfering with the core flow. To minimise friction loss, roughness element heights are kept low relative to duct height. Numerous studies were conducted on ribs in different orientations, such as transverse, angled, V-shaped, and W-shaped.

Prasad and Saini have shown the impact of transverse ribs attached to the absorber plate of the solar air heater duct [52, 53]. For relative roughness pitch (p/e) of 10 and relative roughness (e/D) of 0.033, the greatest increase in friction factor ratio was 4.25 times, while the maximum increase in Nusselt number ratio was 2.38 times when compared to smooth duct. Fig. 14 shows the geometry of the rib roughness. Prasad et al. have looked into similar roughness on three of the solar air heated duct's walls [6]. Roughness on three sides was thought to be more beneficial than roughness on the absorber plate alone.

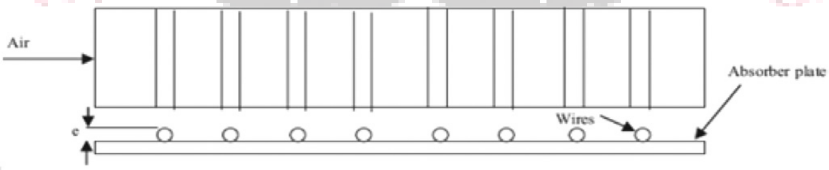

Figure 5: Transverse ribs on absorber plate [52,53].

IV-B Extended surface

In addition to increasing turbulence in the flow, this technique is the most effective since it increases the effective heat transfer area. The expanded surfaces are used as fins in these methods. High pumping power requirements resulted from the large increase in pressure drop caused by extended surfaces. This section discusses the various extended surface types that have been studied.

It was determined that there was a noticeable rise in the pressure drop. Expanded metal was utilised by Saini and Saini [54] to increase the rate of heat transmission (Fig. 26). The relative height of the mesh, the relative shortway length of the mesh, and the relative longway length of the mesh were used to describe the geometry of expanded metal. The corresponding ranges were 0.012–0.039, 15.62–46.87, and 25–71.87, respectively. It was determined that the friction factor and Nusselt number strongly depended on the geometrical characteristics of the expanded metal mesh.

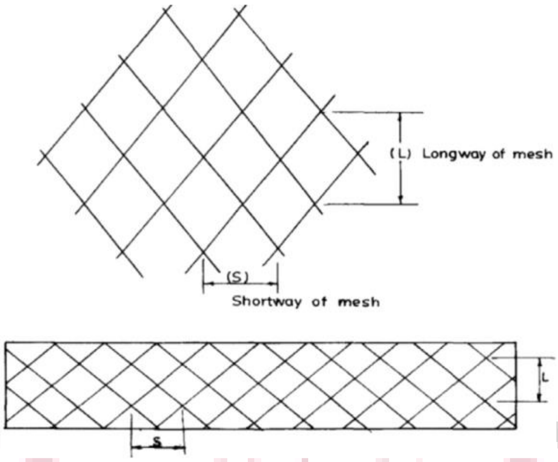

Fig. 26. Expanded metal mesh [54].

The impact of a 45° zigzag Z-baffle in two modes on heat transfer and friction properties was examined by Sriromreum et al. [55]. The baffles' relative height and relative pitch fell between 0.1 and 0.3 and 1.5 and 3, respectively. For in-phase 45° Z-baffles, the Nusselt number and friction factor were considerably increased, as opposed to out-phase 45° Z-baffles. The impact of perforated fins on a rectangular air channel with a cross sectional area of 100–250 mm2 was theoretically shown by Sahin and Demir [56].

IV-C Swirl devices

One of the most promising methods for increasing the rate of heat transmission is the use of swirl devices in the flow. By creating secondary flow in the form of vortices within an existing axial flow, swirl devices thin the boundary layer. The velocity profile close to the walls or surfaces is altered by secondary flow. Numerous swirl devices, such as twisted tape, helical wire, and conical rings, have been utilised and studied in earlier studies.

To increase the rate of heat transmission in solar water heater tubes, twisted tapes were utilised [57]. For varying mass flow rates, the relationship between twist pitch and tube diameter (3–12) was examined. Compared to a smooth tube, this method boosted the rate of heat transfer by 18–70% and the pressure decrease by 87–132%.

Investigations were conducted into the effects of twisted tape thickness (0.5–2 mm) on pressure drop and heat transfer. It was discovered that thick twisted tapes were more efficient at enhancing heat transmission. Jaisankar et al. [58] examined two distinct twisted tapes in solar water heaters: helical and left-right twisted tapes with a twist ratio of three. In contrast to helical twisted tape, which created swirl flow in a single direction along the tube's length, left-right twisted tape resulted in more heat transfer and friction factor.

IV-D Vortex generators (VGs)

The fundamental idea of VGs is to produce longitudinal vortices in the flow direction, which causes secondary flow to form. This fractures or disturbs the thermal boundary layer above the heated surface and transfers the heat to the core flow. Numerous VGs devices, including cans, winglets, barriers, and more, have been studied and are covered here.
Winglet type vortex generators in rectangular air channels were studied by Kotcioglu et al. [59]. The arrangement of the VGs' wings allowed them to interrupt the expanded and contracted channel flow zone. A pair of VGs caused longitudinal vortices, which improved heat transfer by producing a mixing effect in a buffer area between convergent and divergent channels.

Torri et al. [60] examined winglet type VGs in a circular fin-tube heat exchanger (Fig. 44). A hitherto unutilised orientation known as the "common flow up" arrangement was employed. With the winglets, heat transport was enhanced by 10–30% for staggered tube banks. For better tube wake management, Jordan and Jacobi [61] looked into winglet type VGs arrays in a common-flow-up orientation. For a single row winglet arrangement, heat transfer increased from 16.5% to 44%, and for a three-row vortex generator array, heat transfer increased from 29.9% to 68.8%.

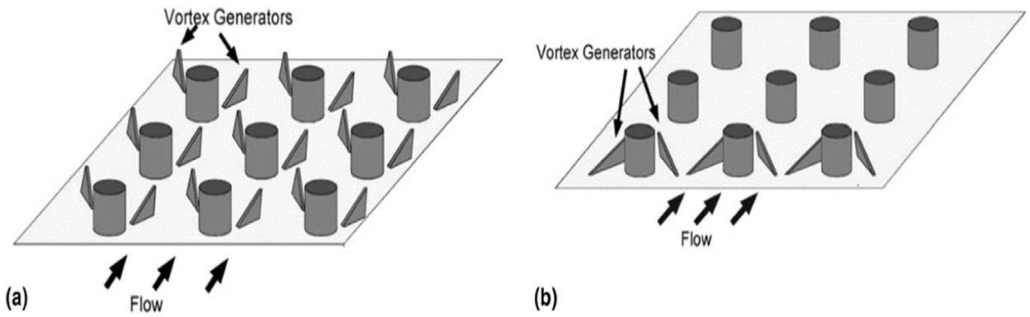

Fig. 26. Winglet type VGs combined with tube bank; (a) Common flow down, (b) Common flow up [60].

V Conclusion

The primary focus of the researcher was either active or passive technique. It is uncommon to combine technique and activity. It has been suggested that the ideal mix of active and passive procedures is the effect of helical coiled wire in heat exchanger tubes utilising ferrofluid in the presence of a magnetic field. Without influencing the core flow, helical wire would disrupt the boundary layer. Magnetic fields would then push the core flow, reducing the pressure drop and improving thermo-hydraulic performance. The majority of researchers reported their findings in terms of friction factor and Nusselt number, and they were contrasted with findings from conventional settings such smooth tubes and smooth ducts, among others. Only a few number of studies presented their findings about the system's critical characteristics of thermal and thermohydraulic performance. When active and passive procedures are used together, a significant amount of energy is needed to promote heat transfer, however these methods are highly costly. The economics of the methods must be investigated in order for them to be used outside of the lab and in actual applications.

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