Journal of Heat and Mass Transfer Research 12 (2025), Serial Number 23, 15 – 28

Semnan University

Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

ISSN:2383-3068

Review Article

Mixed and Forced Convection Heat Transfer in Baffled Channels: A Brief Review

Rabah Henniche *, **Abdelkader Korichi**

Faculty of Technology, Laboratory of Mechanics, Physics, and Mathematical Modeling (LMP2M), University of Medea, Medea, 26000, Algeria

ARTICLE INFO

Article history:

Received: 2024-06-07

Revised: 2024-08-19

Accepted: 2024-08-22

Keywords:

Convective heat transfer enhancement;

Airflow;

Channels;

Baffles;

CFD.

ABSTRACT

Improving heat transfer in thermal systems has become a focus of many research studies due to the critical need for efficient waste of residual heat. The regulation of heat transfer between components in thermal systems has a direct impact on their efficiency and performance. As a result, effective heat management is critical to improving the efficiency of thermal systems and extending the life of their components. It should be noticed that baffles are important structural components widely used in various industrial applications like heat exchangers, solar collectors, electronic cooling, etc. In addition, baffles enhance fluid mixing and heat transfer behaviors. Most industrial systems do not operate in a steady state. In particular, transient phases occur during start-up and shut-down or during the control phase of controlled systems. Thus, in laminar flow, baffles induce flow unsteadiness or help the flow to bifurcate from a steady state to an unsteady flow. This paper treated the effects of different baffle shapes incorporated in channels on heat transfer rate, efficiency and friction factor in mixed and forced convection cases. Various experimental and numerical studies have been carried out on this topic to examine heat transfer enhancement compared to the flow energy. It was noticed that increasing the Reynolds number, blockage ratio and decreasing the Grashof number can achieve an increase in heat transfer. The maximum heat transfer enhancement was obtained for higher blockage ratio and higher Reynolds number in forced convective flow. The highest heat transfer improvement was obtained for the 45° angled baffles (between 150% and 850%). In mixed convective flow, the highest rate of heat transfer was obtained for transverse baffles (2.8 times compared to a similar channel with no baffles). Finally, This comprehensive review is beneficial for researchers focused on flow and heat transfer applications to use other baffle designs and fluids beyond air.

1. Introduction

Recently, the global demand for energy has exploded, driven by industrial progress. The efficient operation of various applications often requires the removal of residual heat to ensure optimum performance and avoid any negative impact on the desired output, for instance, solar collectors, electronics cooling, high power density chips in supercomputers, nuclear reactor cooling systems and other electronic devices [1, 2]. Forced or mixed convection is the most common process used to dissipate residual heat in thermal devices. The coexistence of forced and free convection effects of similar magnitude leads to the development of the mixed convection phenomenon. Due to variations in the thermophysical properties of the fluid and the effects of buoyancy, mixed convection exhibits distinct heat transfer behaviors that differ from those observed in pure forced or free convection. These behaviors add complexity to the overall heat transfer process [2, 3].

*** Corresponding author.**
E-mail address:rabahh200@yahoo.fr

Cite this article as:

Henniche, R. and Korichi, A., 2025. Mixed and Forced Convection Heat Transfer in Baffled Channels: A Brief Review. *Journal of Heat and Mass Transfer Research*, 12(1), pp. 15-28.

https://doi.org/10.22075/JHMTR.2024.34280.1565

In forced convection, fluid movement is induced by mechanical means (such as a pump or fan) regardless of the magnitude and direction of heating. The development of mixed flow in a vertical channel is influenced by the direction of forced versus free convection, resulting in the coexistence of assisted and unfavorable buoyancy effects. These effects result in distinct flow patterns and heat exchange characteristics dictated by the interplay between forced and natural convection. In laminar mixed convection, the presence of buoyancy-assisted flow results in greater heat transfer than that achieved by extremely forced convection. This phenomenon results from the additional convective heat exchange mechanism introduced by buoyancy forces, which increases the overall heat exchange rate in the system. This feature of mixed convection underscores the importance of considering the interactions between flow velocity and buoyancy forces in determining the overall heat exchange performance. In the case of turbulent mixed convection flow, the influence of buoyancy-assisted flow on heat transfer depends on the intensity of the buoyancy forces. When buoyancy is low, it tends to degrade heat transfer due to increased turbulence levels. On the other hand, high buoyancy tends to improve heat transfer by promoting better mixing and increasing convective heat transfer coefficients. Flow against buoyancy always results in increased heat transfer due to increased turbulence. This phenomenon results from the interaction between buoyancy and flow, allowing better mixing of fluids and higher convective heat transfer coefficients, thus improving heat transfer performance [4-7].

In today's modern world, the majority of everyday devices rely on electronic components, which highlights the importance of energy optimization of these systems, especially in the industrial sector. However, the main objective of thermal control systems in electronic devices is to ensure operational stability by maintaining uniform thermal conditions. This means that the thermal system must operate in thermal equilibrium, which is essential to prevent overheating and optimize the performance and lifetime of electronic components. In addition, an effective cooling mechanism must be designed and implemented to ensure that the temperature remains below a specified threshold. In addition, thermal system design criteria must be optimized with the primary aim of achieving the highest possible heat transfer while minimizing pressure drop. This is a critical and highly relevant topic in the field of heat exchangers and electronic devices. This approach aims to achieve efficient heat dissipation that effectively cools electronic components and improves overall system performance [8]. The incorporation of in-line or staggered baffles on the channel walls is a widely used approach to improve convective heat transfer [9]. This comprehensive review provides a summary of published research focused on improving heat transfer in baffled channels, specifically addressing forced and mixed convection scenarios in the case of air as the working fluid. However, the main objective of this paper is to provide a concise and informative overview of the effects of different baffle shapes on heat transfer improvement. In addition, research on mixed convective flows in this area is sparse compared to forced convective flow. Therefore, further research is needed, especially studies on detailed experimental measurements and numerical simulations, in order to obtain the best results useful for the design of efficient thermal systems that can provide maximum heat transfer with minimum flow energy. It was noted that this work summarizes the majority of studies on airflow in channels with various baffle shapes from 1977 to 2024. The authors consider this work to be a base for researchers that helps them to do other future research in this field.

2. Mathematical Formulation

For the fluid flow through the channel the conventional governing equations are the continuity, the Naviere-Stokes equations and the energy equation. In the absence of flow work, viscous dissipation and body forces, the equations governing the motion of an incompressible fluid can be written in the most useful form for the development of the finite volume method:

Conservation of Mass (Continuity Equation):

$$\nabla.\left(\vec{V}\right) = 0 \tag{1}$$

Momentum Equation (Navier-Stokes):

$$\rho\left(\vec{V}.\nabla\vec{V}\right) = \rho\vec{g} - \nabla p + \mu\,\nabla^2\vec{V} \tag{2}$$

Energy Equation:

$$\rho c_p(\vec{V}.\nabla T) = k\nabla^2 \mathrm{T} \tag{3}$$

in these equations $\vec{V}$ is the local velocity in the domain, while T and p are local pressure and temperature, respectively. Parameters ρ, μ, c_p, g and k are fluid density, dynamic viscosity, specific heat capacity, gravitational acceleration and thermal conductivity of the fluid. The term $\rho\vec{g}$ in momentum equation must be added only in the case of mixed convection.

3. Mixed Convection Heat Transfer in Baffled Channels

Some works investigated the effects of vortex generators such as fins, ribs, and baffles arranged in arrays on mixed convective flow in a variety of physical contexts. Noteworthy studies on the enrichment of heat transfer in laminar airflow in channels with baffles are cited below.

Cheng et al. [10] and Cheng and Yang [11] carried out a numerical study of convective heat transfer with assisted flow in a heated channel with baffles attached to the heated wall (Figures 1 and 2). Their findings indicate that a number of recirculation zones are formed near the cold wall under high heating conditions, and at a low Grashof number heat transfer was accurately predicted by the pure forced convection estimate. Their results further suggest that the heat transfer rates were directly influenced by both the baffle heights and the Reynolds number. Consequently, at a high Grashof number, the buoyancy effect becomes appreciable and hence, it should be taken into account in the mathematical model. In addition, the buoyancy effect on the flow is the strongest when the channel is arranged to be vertical.

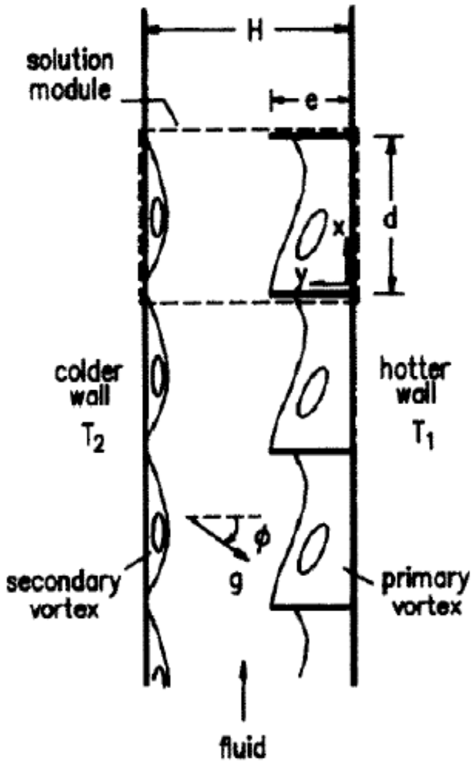

Fig. 1. A vertical parallel-plate channel with baffles [10]

Chang and Shiau [12] numerically simulated the impact of one baffle secured to the adiabatic wall of a channel on heat transfer behavior under opposing buoyancy force, as exposed in Figure 3. Their findings elucidate that the channel with both flow pulsation and a baffle generates a better heat transfer rate. They concluded that the dimensionless pulsating frequencies St = 0.333 and 0.25 could be considered to be the natural frequency of the physical systems. Fu et al. [13] conducted a computational study of laminar mixed convection inside a three-dimensional vertical channel containing a slender moving obstacle aligned with the flow axis to investigate the enhancement of heat transfer. They show that the heat transfer rate increases with increasing Reynolds number and decreases with the ratio of $Ri = Gr/Re^2$ due to the stronger interaction between the moving block and the channel flow. However, a contrary- phenomenon was observed at a higher Richardson number (Ri) because the stronger buoyancy force impedes the slow channel flow from touching the heating surface and a lower level of heat transfer was obtained.

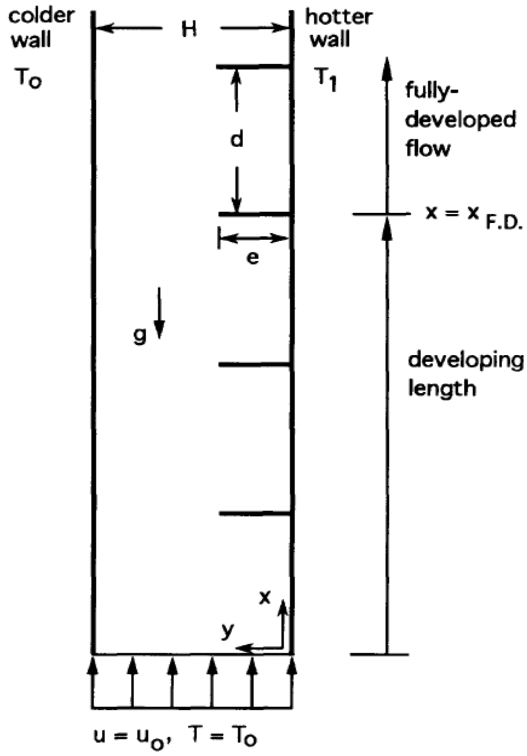

Fig. 2. A vertical channel with baffles [11]

Nemitallah and Zohir [8] performed a numerical study of laminar mixed convective flow to investigate the effect of baffles connected to the heated wall of a vertical duct on the extent of heat exchange. The Fluent 6.2 package was used to perform CFD calculations in the 2D domain via finite volume formulation. The results are expressed as a function of baffle height and Gr/Re^2 ratio. It can be seen that when the ratio of baffle height to channel width is 10% and 30%, a higher level of heat transfer is achieved compared to the flow energy. They also show that thermal radiation occurs when the Grashof number is large. In addition, when the Gr/Re^2 ratio exceeds a certain threshold, a favorable pressure gradient develops along the channel axis, leading to the formation of a recirculation zone near the cold wall. Mixed laminar convective flow in a three-dimensional square channel with a baffle attached to the unheated wall has been the subject of a numerical study by Chang [14], who discovered that when the density-driven flow is substantial, a backflow region develops near the top wall and the heated surface. However, the flow restriction induced by the baffle can increase the flow velocity and consequently increase the level of heat transfer. The author also points out that the increase in heat transfer varies depending on the placement of the baffle and the occurrence of a backflow region.

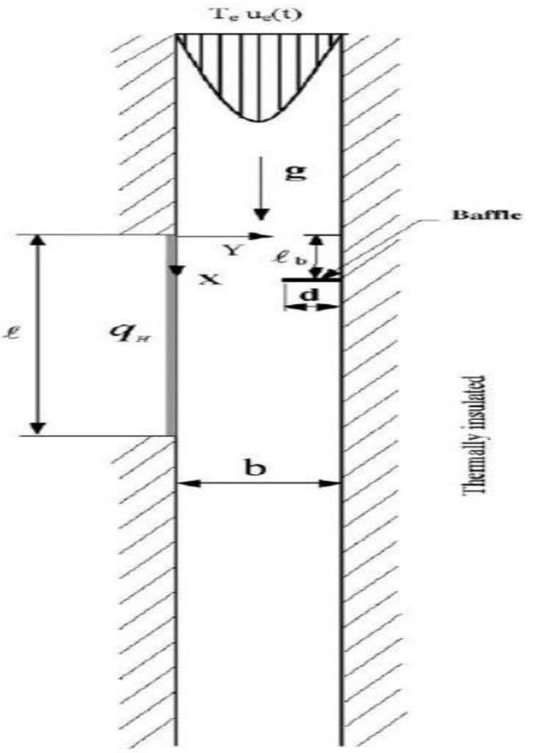

Fig. 3. Diagram of physical system [12]

Henniche and Korichi [15] examined the combined features of laminar flow and convective heat transfer in a vertical channel with alternating baffles positioned on both walls, as displayed in Figure 4. OpenFOAM, an open-source finite volume CFD code, was used to solve the governing equations. The study shows that the heat transfer extent for the oscillating flow is about 2.8 times larger than that of the equivalent channel without baffles when the baffle height is 0.25. However, this particular baffle height strikes a favorable balance between heat transfer efficiency and flow energy requirement. When the alternating baffles are tilted in the flow direction, another computational analysis is performed by Henniche and Korichi [16]. They perceived that the increase in heat transfer level and friction factor varies proportionally with the Reynolds number and inversely with the Grashof number. In addition, they showed that the efficiency index η increases with the Grashof number, but an increase in the Reynolds number or baffle tilt angle γ decreases it. Boruah et al. [17] presented a numerical study aimed at exploring the thermohydraulic properties and entropy production in the circumstance of mixed convective flow through a backward stepped channel containing a baffle. The influence of different baffle shapes (square, triangular and elliptical) on the pressure drop, entropy production, local and mean Nusselt number was investigated over a Richardson number Ri ranging from 0.1 to 1 while keeping the Reynolds number Re = 100 constant. The results show that the use of staggered elliptical baffles improves thermal efficiency, reduces pressure drop, and minimizes entropy production compared to other baffle configurations. The authors suggest that the choice of staggered elliptical baffles represents the optimal design decision when evaluating both thermal-hydraulic performance and entropy production.

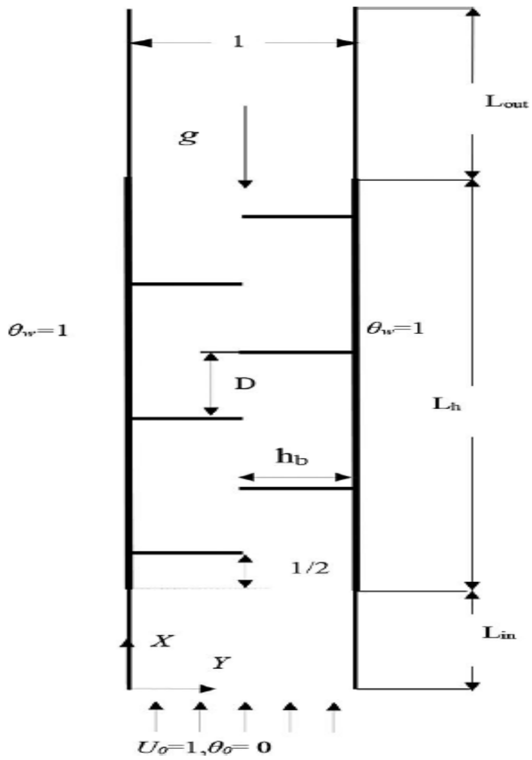

Fig. 4. Diagram of the physical domain [15]

The effect of another type of baffles, such as flexible baffles, on heat transfer enhancement has been investigated by Yaseen and Ismael [18]. They examined non-Newtonian mixed convection heat transfer within an open trapezoidal cavity using fluid-structure interaction (FSI). Their research focused on two-dimensional, incompressible, laminar, and unsteady fluid flow over a flexible baffle mounted on the cavity's top wall, as described in Figure 5. They showed that the average Nusselt number increases as the power-law index decreases and decreases as the Cauchy number rises for shear-thickening fluid in all ranges of Richardson number. Then, Yaseen and Ismael [19] examined how the position of a flexible baffle affects the heat transfer rate. Their results indicated that the proposed baffled channel significantly improves heat transfer. Yaseen and Ismael [20] studied the deflection and stress induced by a baffle used to improve heat transfer in an open trapezoidal cavity. The results revealed that the flexible baffle is less stressed than the stiffer one, while the heat transfer can be increased by 44% with a flexible baffle at Re = 400.

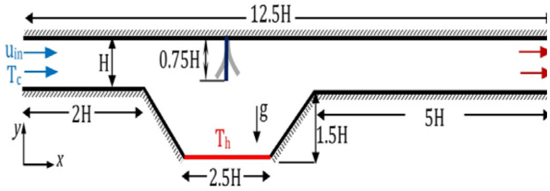

Fig. 5. Physical domain and coordinates system[18]

4. Forced Convection Heat Transfer in Baffled Channels

A variety of research investigations have explored the effect of vortex generators such as fins, ribs, and baffles on forced convective flow in various physical settings. Notable investigations on improving heat transfer in channels with baffles and using air as the working fluid will be outlined in two segments: numerical and experimental analyses.

4.1. Numerical Studies

In a baffled channel, the periodically developed flow pattern, characterized by alternating baffles attached to both walls, is observed as the flow progresses beyond the inlet. This event was the subject of a numerical study by Patankar et al. [21], Webb and Ramadhyani [22], and Kelkar and Patankar [23] numerically studied forced convective flow in a rectangular channel to which baffles are attached in a staggered fashion on upper and lower walls. The study shows that as the Prandtl number increases, there is an increase in heat transfer level and comparatively low resulting friction factor. Additionally, Lopez et al. [24] found that the amount of heat transfer increases as the impedance ratio or thermal conductivity of the baffle increases. They also observed that for a drag ratio of 0.5, the three-dimensional effects could not be ignored, even at low Reynolds numbers and low dimensional ratios. The effect of porous and solid baffles in a rectangular channel under steady-state laminar conditions has been studied by Santos and Lemos [25] and Zhang et al. [26] their results show that a similar amount of heat transfer can be achieved with both perforated and solid baffles. However, solid baffles increase flow resistance while porous baffles decrease it. Guo and Anand [27] investigated the heat transfer in a channel with a single baffle acting as a vortex generator in the entrance region. They found that the heat transfer on the front surface of the baffle was significantly higher than on the back surface due to the impact of the flow. Da Silva Miranda and Anand [28] numerically analyzed the behavior of 2D laminar forced convective flow and heat transfer in a channel containing sixteen perforated baffles placed alternately on both walls. The study was carried out for 100 < Re <400, Darcy number (Da) equal to 8.783×10^{-6}, 1.309×10^{-5}, and 1.79×10^{-5}; dimensionless baffle spacing equal to 11, 13, and 15; thermal conductivity ratios equal to 1, 10, and 100; dimensionless baffle aspect ratio equal to 4, 6, and 12; and dimensionless baffle height set to 1/3. A numerical approach was used to solve the governing model equations. The partial differential equations were discretized using a finite volume method. The results indicate that perforated baffles provide lower heat transfer rates compared to equivalent solid baffles. In addition, the heat transfer rate increases with increasing Reynolds number, conductivity ratio, and dimensionless baffle distance, while it decreases with Darcy number and baffle aspect ratio. For both perforated and solid baffles, the thermal efficiency ratio is less than unity. Guzmán and Del Valle [29] presented a numerical study to investigate the flow transition situation and heat transfer characteristics in a grooved channel when the flow bifurcates from a steady state to an unsteady regime.

Figure 6 illustrates the transition from steady to quasi-periodic flow. The results show that the average heat transfer rate remains relatively constant in the steady state but gradually increases in the unsteady regime. In the quasi-periodic flow regime, the heat transfer rate exceeds that of the periodic flow regime. This increase is twice as great in the periodic flow and two and a half times greater in the quasi-periodic flow compared to a similar channel with no baffles.

Mousavi and Hooman [30] conducted a numerical investigation to study the heat transfer characteristics and laminar fluid flow in the entrance region of a two-dimensional channel with uniformly heated walls and alternating baffles placed on the two walls, as depicted in Figure 7. The finite volume method was used to discretize the governing equations. Results were presented for Reynolds numbers ranging from 50 to 500, baffle heights in the range of 0 to 0.75, and Prandtl numbers ranging from 0.35 to 10. They found that the evolution of the flow periodicity is influenced not only by the Reynolds number and the blockage ratio but also by the Prandtl number. A numerical study by Saleh et al. [31] investigated the heat transfer behaviors and turbulent flow phenomena in a channel with dual baffles mounted on both lower and upper walls, as illustrated in Figure 8. Fluent software with finite volume formulation was used to simulate fluid flow and heat transfer within the computational domain. The outcomes demonstrate that perforated baffles facilitate the creation of vortex flow, effectively stirring the stagnant flow in the downstream region. This stirring significantly improves the heat transfer rate, resulting in an increase in thermal efficiency ranging from 9.78 to 18.43%.

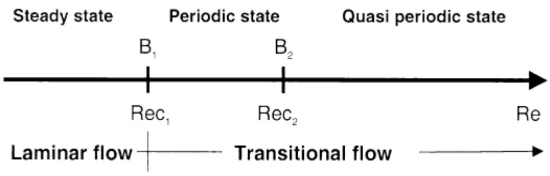

Fig. 6. Passage from steady to quasi periodic flow by two consecutive Hop stabilities, $Re_{c1} = 549$ and $Re_{c2} = 860$ [29]

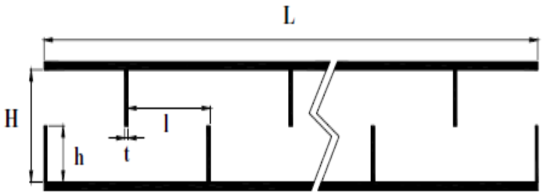

Fig. 7. Physical coordinate system [30]

Compared to 90° transverse baffles, in terms of heat transfer characteristics and laminar periodic flow through a rectangular channel, Promvonge et al. [32] found that the 45° tilted baffles resulted in a significant increase in heat transfer rate, ranging from 150% to 850%, over a blockage ratio (BR) in the range of 0.05 to 0.3. However, with 45° inclined baffles, the increase in heat transfer was approximately 100 to 200% greater than with 90° baffles, while the coefficient of friction decreased by approximately 10 to 150%. Kwankaomeng et al. [33] investigated the effect of 30° inclined baffles on heat transfer and pressure drop at blockage ratios ranging from 0.1 to 0.3. The results show that the use of 30° inclined baffles increased the heat transfer rate by 100% to 650%. However, this increase in heat transfer was accompanied by a significant increase in pressure drop, ranging from 1 to 17 times compared to the identical channel with no baffles. In another investigation, Promvonge et al. [34] studied laminar flow in a channel with 30° tilted baffles at various pitch and blockage ratios. The results show that 30° tilted baffles result in a significant increase in heat transfer rate.

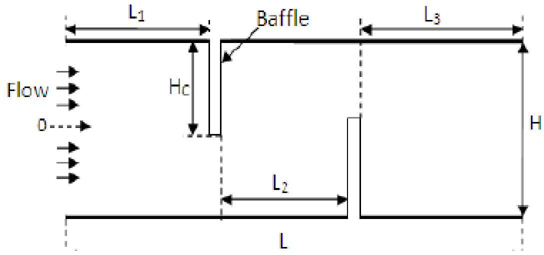

Fig. 8. Channel geometry [31]

Promvonge et al. [35] found that staggered diamond-shaped inclined baffles with angles ranging from 5 to 35° improved heat transfer by 200% to 280% over Reynolds numbers ranging from 100 to 600. However, this improvement is associated with a friction factor that was between 20 to 220 times higher than that obtained in a similar channel without baffles. Kamali et al. [36] investigated the effect of four different baffle configurations on improving cooling efficiency in the gas turbine sector. The numerical methodology used in this study is an independent solution algorithm using the finite volume technique. The results indicate that trapezoidal baffle configurations provide a superior improvement in heat transfer rate and reduced friction factor compared to alternative configurations when the Reynolds number falls between 8000 and 20000.

CFD was used by Kumar and Kim [37] to evaluate the overall effect of different V-rib arrangements in airflow heat exchangers. The results indicate that the use of finned V-ribs results in the highest thermal performance. Fawaz et al. [38] performed a numerical analysis of periodic fully developed flow and thermal features within a V-shaped baffle channel over a Reynolds number (Re) in the range of 5000 to 25000. The study included baffle heights (BR) of 0.2, 0.4, and 0.6 and baffle pitch ratios (PR) of 0.5, 1, and 1.5. In this study, the governing equations were solved using the finite volume formulation, and ANSYS Fluent 16.0 was used to investigate the flow structure and thermal performance in the computational domain. Figure 9 shows the influence of the pitch and blockage ratios on the thermal efficiency (η) as a function of Re. The results indicate that the thermal performance or thermal efficiency η tends to decrease with increasing Reynolds number (Re) for all blockage ratios (BR). Furthermore, higher values of η were achieved as the BR decreased. For example, at BR = 0.2, the η value is approximately 0.78 at the lower Re = 5000. In addition, at BR = 0.4, it was observed that at BR = 0.5, a higher value of thermal efficiency (η) of about 0.68 was obtained at Re = 5000.

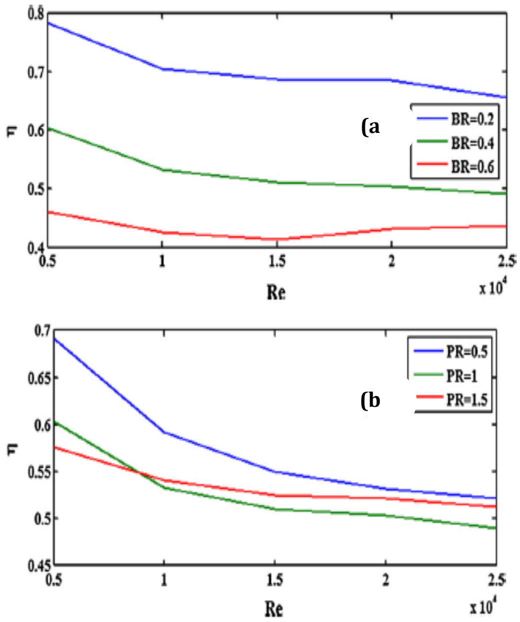

Fig. 9. Thermal performance as function of: (a) Blockage ratio, (b) Pitch ratio [38]

Ismael [39] reported a numerical study to evaluate the improvement of heat transfer in forced convection airflow in a partially heated channel. The channel had a flexible segment integrated on the upper wall, accompanied by upstream and downstream baffles acting as vortex generators and surrounding the flexible segment, as depicted in Figure 10. In this investigation, the dilemma is framed using the Arbitrary Lagrangian-Eulerian (ALE) approach rooted in the finite element method. It was observed that the peak thermal efficiency was achieved when the lengths of the upstream and downstream baffles were 0.6 and 0.2, respectively. Furthermore, the results indicate that the presence of the flexible wall segment decreased the thermal efficiency of the non-baffled channel. Additionally, It was also found that the Nusselt number of a certain compliant baffled channel enhances 94% compared with the non-baffled channel at Re = 250, while the pressure drop increases by 210%. Lin et al. [40] conducted the analysis of fluid flow in heat exchangers with and without the presence of vortex generators. Two-dimensional CFD simulations of steady-state and transient flow were analyzed. ANSYS Fluent was used to simulate the fluid flow. The results show that the inclusion of vortex generators increased the heat transfer by 21.46% in a steady flow and 29.45% in the oscillating flow. Al-Juhaishi et al. [41] carried out a numerical study aimed at improving the heat transfer in a curved channel with a rectangular cross-section by using inclined baffles with special geometries.

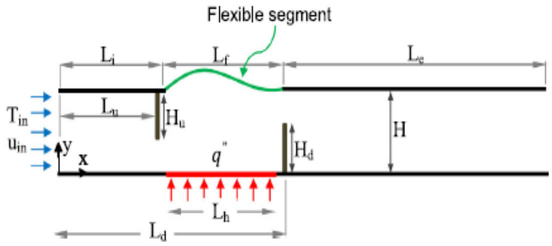

Fig. 10. Physical problem and coordinates system [39]

The results show that the optimum level of heat transfer was achieved at the angle of α = 90°, with 13 baffles and a Reynolds number of 5000. In addition, the increase in heat transfer was in the range of 2.5 to 3.8 times compared to the non-baffled channel. Under the same conditions, the maximum efficiency index reached 4.4, as shown in Figure 11. Phu and Thao [42] presented a numerical study of an inclined flat tube heat exchanger equipped with baffles. They investigated how the tilt angle of the flat tube and the Reynolds number affect the thermohydraulic efficiency. Their results indicate that the highest thermohydraulic efficiency is 0.0405, which occurs at a Reynolds number of 1300 and a tube tilt angle of 15°.

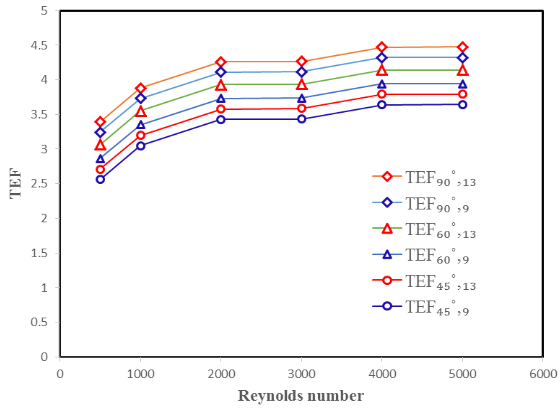

Fig. 11. Efficiency index in relation of Reynolds number [41]

CFD was used by Boonloi and Jedsadaratanachai [43] to study the forced convection turbulent flow and heat transfer behaviors in a heat exchanger equipped with separate combined baffles within the Reynolds number ranging from 5000 to 20000. The governing equations were solved using the finite volume method, and Fluent software was used to simulate the flow and heat transfer within the computational domain. The heat transfer rate was increased by a factor of 2.8 to 6 compared to the non-baffled channel, depending on the baffle height, Reynolds number, and V-shape orientations. In addition, numerical simulations indicate that the peak thermal efficiency reached approximately 1.72 when the baffle height was 0.1, the Reynolds number was 3000, and the V-baffles were oriented in the flow direction. In another study, Boonloi and Jedsadaratanachai [44] investigated three-dimensional laminar flow and forced convective heat transfer of a fluid moving through a heat exchanger. In this investigation, various configurations of double-V baffles were considered within a Reynolds number ranging from 100 to 2000. The results were expressed in terms of heat transfer rate, friction factor, and thermal efficiency improvement. The maximum Nusselt number ratio and the highest thermal efficiency obtained were 22.42 and 3.55, respectively. In addition, Boonloi and Jedsadaratanachai [45] conducted a numerical simulation that investigated forced convection heat transfer and laminar fluid flow in a channel equipped with various modified corrugated baffles acting as vortex generators. The CFD analysis evaluated the effects of baffle heights, flow directions, and baffle geometries, and the authors found that the peak thermal efficiency was approximately 3.7 over the entire Reynolds number range studied (100 ≤ Re ≤ 200). Saha et al. [46] studied the various characteristics of turbulent airflow and heat transfer phenomena in a rectangular duct with trapezoidal baffles attached to both walls and along its central axis. The governing equations were solved using the finite volume method, and Fluent software was used to visualize the simulation results. It has been observed that increasing Reynolds number (Re) results in higher average Nusselt number (Nu) values and friction factor. In addition, the installation of the initial baffle improves heat transfer by increasing backflow length, which promotes heat exchange. The Nu(x) value was also found to peak at the end of the baffle. Ultimately, they concluded that the simulation results will help researchers in designing and observing flow phenomena in various industrial applications. Recently, Cyriac and Bhusnoor [47] performed a numerical analysis to examine the enhancement of heat transfer rate in a rectangular channel of aspect ratio 6 and obstructions of different geometry (triangular, rectangular and arc) for different pitch ratios and for Reynolds number ranging from 5000 to 20000. They found that the maximum thermal enhancement factor (TEF) of 1.27, 1.08 and 1.05 were obtained for delta, rectangular and arc flow obstacles, respectively. Lazim and Ismael [48] reduced and regulated the temperature of battery cells by installing differently arranged flexible baffles on the channel walls and studying the different arrangements of baffles. They found that the staggered arrangement of baffles was the most efficient configuration, with a maximum temperature difference between battery cells of only 1.85°C at the space between batteries S = 1mm.

4.2. Experimental Studies

The phenomenon of fully developed flow in the context of forced convection flow in a channel equipped with staggered baffles attached to both walls has been experimentally investigated by Berner et al. [49] their results show that laminar behavior is expected at a Reynolds number below 600. Under these conditions, they also found that vortex shedding did not occur. Habib et al. [50] conducted an experimental investigation to analyze the turbulent flow characteristics and heat transfer through a channel with alternating baffles. Their results show that the local and average heat transfer parameters increase with increasing Reynolds number and baffle height. In addition, an increase in the baffle height results in a proportional increase in the pressure drop. However, the associated increase in the pressure loss was found to be much higher than the increase in the heat transfer coefficient. Ko and Anand [51] conducted experimental measurements to investigate heat transfer characteristics and fluid flow in a heated channel equipped with perforated baffles attached to both walls, as shown in Figure 12. The results indicate that the use of porous baffles increases the heat transfer rate by more than 300% compared to a similar non-baffled channel. However, this increase in heat transfer is accompanied by an increase in flow energy. Consequently, an increase in (Re) results in a decrease in heat transfer rate. Dutta and Dutta [52] and Dutta and Hossain [53] conducted an experimental study to investigate the heat transfer properties and fluid flow in a channel with inclined solid and perforated baffles. They concluded that the use of perforated baffles resulted in a significant improvement in heat transfer compared to solid baffles. However, the effectiveness of heat transfer depends on the size, placement, and orientation of the baffles. Inclined perforated baffles exhibit superior efficiency compared to an analogous configuration of solid baffles. In order to experimentally and numerically investigate the heat transfer behavior and friction factor flow in a channel with baffles arranged in a zigzag pattern (see Figure 13), as the Reynolds number Re ranges from 4400 to 20400, Sriromreun et al. [54] found that the performance index decreases with increasing Reynolds number, spacing, and baffle height. Nevertheless, the computational results were in close agreement with the experimental results. Nanan et al. [55] conducted computational and experimental evaluations to investigate the behavior of turbulent forced convection flow and heat transfer in a channel equipped with baffles. They also investigated the effect of the pitch ratio ranging from 1 to 2 and the Reynolds number ranging from 6000 to

20000. Their results show that the heat transfer rate, frictional flow, and efficiency index increased as the Reynolds number increased and the pitch ratio decreased. Kumar et al. [56] experimentally investigated the heat transfer, pressure drop, and thermo-hydraulic characteristics in an airflow channel with multiple V-shaped baffles and found that the greatest improvement in overall thermal efficiency was achieved with a discrete spacing of 0.67, a blockage ratio of 0.5, a spacing width of 1, a baffle spacing of 10, and an angle of attack of 60°. The effect of baffles arranged in different configurations with different perforation ratios on heat exchange, friction factor, and efficiency index within a rectangular channel at a Reynolds.

number ranging from 12000 to 32000 has been reported numerically and experimentally by El Habet et al. [57] The results indicate that the different baffle configurations resulted in an increase in heat transfer rate from 15% to 310% compared to a similar channel without baffles. However, the staggered arrangement exhibited a lower friction factor and higher thermal efficiency than the in-line configuration over the entire Reynolds number spectrum. Kurian et al. [58] conducted an experimental investigation of flow dynamics in jet impact systems using segmented and perforated baffles. Their results showed that the segmented configuration provided the highest heat transfer rate compared to the perforated configuration at all lower ratios. However, the segmented configuration experienced a significant pressure drop despite the increased heat transfer. Similarly, the louvered shape mitigated pressure drop and heat transfer compared to the segmented shape. They concluded that reducing the distance between the jet and the deflector resulted in a significant improvement in thermal-hydraulic performance.

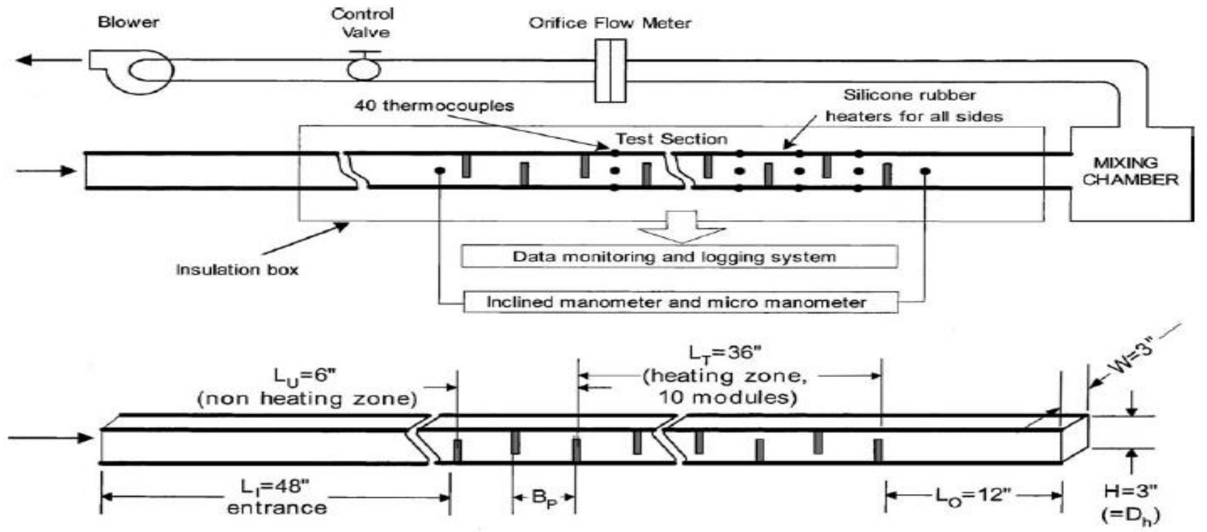

Fig. 12. Schematic diagram of the experimental setup [51]

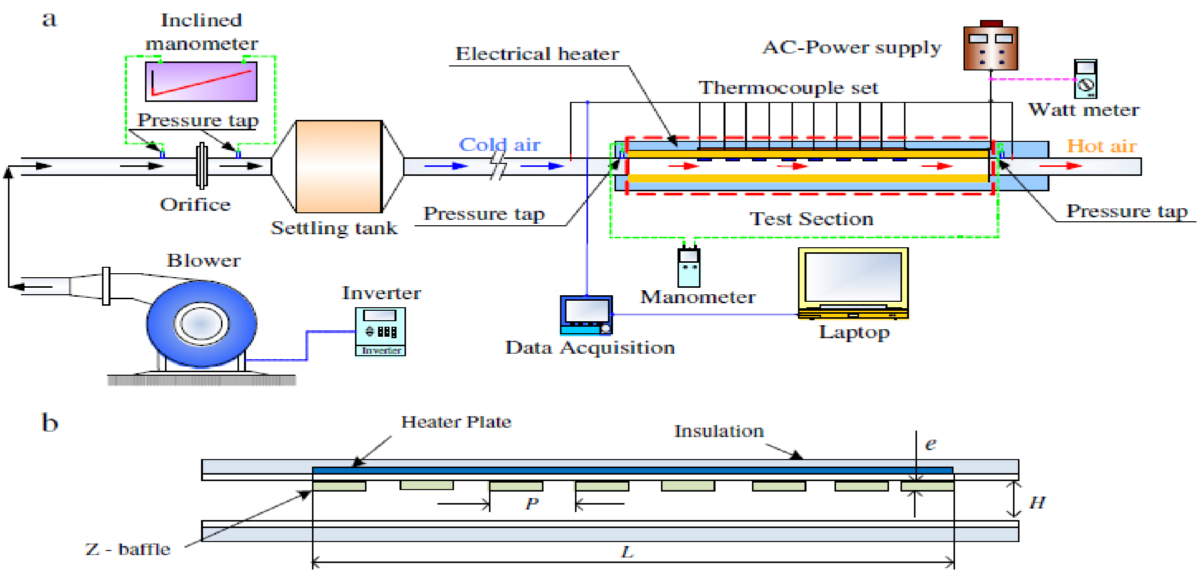

Fig. 13. (a) Schematic diagrams of experimental apparatus, (b) test section [54]

Eiamsa-ard et al. [59] investigated the effect of delta-wing V-baffles on mean Nusselt number, local Nusselt number distribution, pressure loss, and thermal performance within a duct with Reynolds numbers ranging from 6000 to 24000. The geometric characteristics of the delta-wing V-baffle were investigated in terms of relative blockage and pitch ratios (BR = 0.3 and PR = 1.5), as well as five delta-wing angles of attack (θ =0°, 22.5°, 45°, 67.5°, and 90°). Experimental results indicated that smaller delta-wing angles of attack (θ) resulted in increased heat transfer and friction factor compared to larger θ values. In addition, the Nu/Nu_s ratio tended to increase as the Reynolds number decreased. The Nusselt number shows a significant increase when a delta-wing V-shaped baffle is used, as shown in Figure 14.

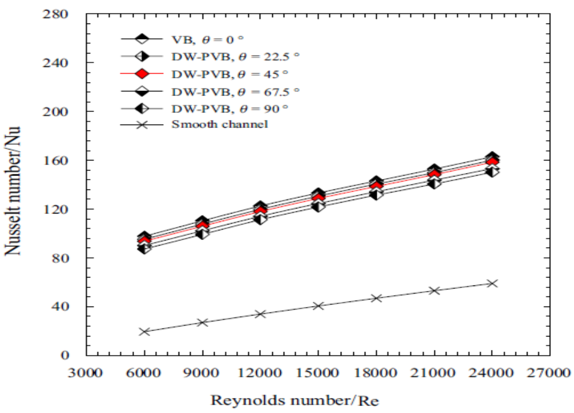

Fig. 14. Influence of attack angle θ at various Re on the average Nusselt number [58]

5. Conclusions

This document provides a comprehensive review of the passive technique used to enhance heat transfer in channels with different baffle shapes, acting as vortex generators and using air as the working fluid. In the course of the present study, the researchers have extensively studied the effects of operating and geometrical parameters. In mixed convection flow, some numerical studies were carried out (22%), but no experimental studies were reported (0%). However, In forced convection flow, many numerical studies were performed (56%), but a few experimental studies were examined (22%). Then, more experimental studies are required to justify the numerical results and implement this technique in engineering applications. The future focus of the researchers is to use other baffle shapes to enhance the heat transfer rate during mixed and forced convection in channel geometry and to study the unsteady flow in this area to have a better enhancement of heat transfer. In addition, researchers need to explore fluids other than air for mixed and forced convection flow in this area to analyze the effect of Prandtl number (Pr). Finally, the results gained from the aforementioned analyses lead to the following conclusions:

i. Better heat transfer enhancement is obtained for 45° angled baffles in the case of forced convection flow.

ii. Heat transfer efficiency was increased by increasing Reynolds number and decreasing Grashof number.

iii. The highest heat transfer improvement was obtained 2.8 times compared to the similar channel without baffles in the case of mixed convection flow.

iv. Heat transfer increases with increasing either baffle height or baffle spacing.

v. Porous baffles reduce the friction factor compared to solid baffles.

vi. Heat transfer rate was influenced by the dimensions, location, and orientation of the baffles with respect to the flow direction.

vii. Flexible baffles can improve heat transfer higher than stiffer baffles for a specific configuration.

Nomenclature

ALE	Arbitrary Lagrangian-Eulerian
BR	Blockage ratio
CFD	Computational fluid dynamics
Gr	Grashof number
Nu	Average Nusselt number
Nu(x)	Local Nusselt number
Nu_s	Average Nusselt number for smooth channel
PR	Pitch ratio
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
TEF	Thermal enhancement factor

Greek symbols

θ	Delta-wing attack angle
γ	Baffle titled angle

Subscripts

s	Refers to smooth channel

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

References

[1] Husain, S., Adil, M.d., Arqam M., Shabani, B. A., 2021. Review on the thermal performance of natural convection in vertical annulus and its applications. *Renewable Sustainable Energy Reviews*, 150, p.111463.

[2] Husain, S., Khan, S.A., 2021. A review on heat transfer enhancement techniques during natural convection in vertical annular geometry. *Cleaner Engineering and Technology*, 5, p. 100333.

[3] Kim, S.Y., Kim, C.S, Cho, H.K., 2021. Local flow structure and turbulence quantities inside a heated rectangular riser in turbulent forced and mixed convection heat transfers. *Experimental Thermal and Fluid Science*, 122, p.110297.

[4] Chae, M.S., Chung, B.J., 2014. Laminar mixed convection experiments in horizontal pipes and derivation of a semi-empirical buoyancy coefficient. *International Journal of Thermal Sciences*, 84, pp. 335–346.

[5] Shin, D.H., Kim, S.Y., Kim, C.S., Park, G.C., Cho, H.K., 2019. Development of a heat transfer coefficient correlation for buoyancy-aided turbulent mixed convection of air inside a vertical channel. *Applied Thermal Engineering*, 159, p.113884.

[6] Chae, M.S., Chung, B.J., 2019. Experimental study on local variation of buoyancy-aided mixed convection heat transfer in a vertical pipe using a mass transfer method. *Experimental Thermal and Fluid Science*, 104, pp. 105–115.

[7] Chae,M.S., Chung, B.J., 2020. Variations in buoyancy-aided turbulent mixed convective heat transfer along a vertical rectangular channel. *International Communications in Heat and Mass Transfer*, 118, p.104906.

[8] Nemitallah, M.A., Zohir, A.E., 2016. Investigations of Heat Transfer, Entropy Generation and Pressure Build Up for Upward Flow in a Vertical Channel Equipped with a Fin Array. *Heat and Mass Transfer*, 52, pp. 1953–1961.

[9] Nabou, M., Bouhadef, K., Zeghmati, B., Daguenet, M., 2008. Numerical Study of Laminar Forced Convection in Entrance Region of a Wavy Wall Channel. *Numerical Heat Transfer, Part A: Applications*, 53, pp. 35–52.

[10] Cheng, C.H., Luy, C.D., Huang, W.H., 1992. Buoyancy Effect on the Heat Convection in Vertical Channels with Fin Array at Low Reynolds Numbers. *International Journal of Heat and Mass Transfer*, 35(10), pp. 2643–2653.

[11] Cheng, C.H., Yang, J.J., 1994. Buoyancy-Induced Recirculation Bubbles and Heat Convection of Developing Flow in Vertical Channels with Fin Arrays. *International Journal of Heat and Fluid Flow*, 15 (1), pp.11–19.

[12] Chang, T.S., Shiau, Y.H., 2005. Flow Pulsation and Baffle's Effects on the Opposing Mixed Convection in a Vertical Channel. *International Journal of Heat and Mass Transfer*, 48 (19–20), pp. 4190–4204.

[13] Fu, W.S., Huang, J.C., Wang, Y.Y., Huang, Y., 2013. Enhancement of Heat Transfer of Mixing Convection in a Vertical Channel by a Moving Block. *Journal of Mechanics*, 29 (1), pp. 95–107.

[14] Chang, T.S., 2015. Enhanced Three-Dimensional Mixed Convection in a Horizontal Channel Using a Baffle. *Heat Transfer Engineering*, 36(17), pp. 1426–1435.

[15] Henniche, R., Korichi, A., 2017. Heat transfer enhancement in self-sustained oscillatory flow in a staggered baffled vertical channel under the buoyancy effect. *Numerical Heat Transfer, Part A: Applications*, 71(12), pp. 1189-1204.

[16] Henniche, R., Korichi, A., 2021. Enhanced Mixed Convection in a Vertical Channel by Addition of Staggered Inclined Baffles. Journal of Thermophysics and Heat Transfer, 35(1), pp. 114-126.

[17] Boruah, M.P., Randive, P.R., Pati. S., 2018. Hydrothermal Performance and Entropy Generation Analysis for Mixed Convective Flows over a Backward Facing Step Channel with Baffle. International Journal of Heat and Mass Transfer, 125, pp. 525–542.

[18] Yaseen, D.T., Ismael M.A., 2020. Analysis of power law fluid structure interaction in an open trapezoidal cavity. International Journal of Mechanical Sciences, 174, p.105481.

[19] Yaseen, D.T., Ismael M.A., 2020. Effect of deformable baffle on the mixed convection of non-Newtonian fluids in a channel-cavity. Basrah Journal for Engineering Sciences, 20(2), pp. 18–26.

[20] Yaseen, D.T., Ismael M.A., 2023. Structural mechanics of flexible baffle used in enhancing heat transfer of power law fluids in channel-trapezoidal cavity. Experimental Techniques, 47, pp. 37–46.

[21] Patankar, S.V., Liu, C.H., Sparrow, E.M., 1977. Fully Developed Flow and Heat Transfer in Ducts Having Streamwise-Periodic Variations of Cross-Sectional Area. Journal of Heat and mass Transfer, 99(2), pp. 180–186.

[22] Webb, B.W., Ramadhyani, S., 1985. Conjugate Heat Transfer in a Channel with Staggered Ribs. International Journal of Heat and Mass Transfer, 28 (9), pp. 1679–1687 .

[23] Kelkar, K.M., Patankar, S.V., 1987. Numerical Prediction of Flow and Heat Transfer in a Parallel Plate Channel with Staggered Fins. Journal of Heat and Mass Transfer ,109(1), pp. 25–30.

[24] Lopez, J.R., Anand, N.K., Fletcher, L.S., 1996. Heat Transfer in a Three-Dimensional Channel with Baffles. *Numerical Heat Transfer, Part A: Applications*, 30, pp. 189–205.

[25] Santos, N.B., de Lemos, M.J.S., 2006. Flow and Heat Transfer in a Parallel-Plate Channel with Porous and Solid Baffles. *Numerical Heat Transfer, Part A: Applications*, 49(5), pp. 471–494.

[26] Zhang, H.J., Zou, Z.P., Shao, F., Song, S.H., 2015. Investigations of Heat Transfer Enhancement in a Channel with Staggered Porous Ribs by the Preconditioned Density-Based Algorithm. *Numerical Heat Transfer, Part A: Applications*, 67(12), pp. 1370–1385.

[27] Guo, Z., Anand, N.K., 1997. Three-dimensional heat transfer in a channel with a baffle in the entrance region. *Numerical Heat Transfer, Part A: Applications*, 31(1), pp. 21-35.

[28] Da Silva Miranda, B.M., Anand, N.K., 2004. Convective Heat Transfer in a Channel with Porous baffles. *Numerical Heat Transfer, Part A: Applications*, 46 (5), pp. 425-452.

[29] Guzman, A.M., Del Valle, M., 2006. Heat Transfer Enhancement in Grooved Channels due to Flow Bifurcations. *Heat and Mass Transfer*, 42 (11), pp. 967–975.

[30] Mousavi, S.S., Hooman, K., 2006. Heat and Fluid Flow in Entrance Region of a Channel with Staggered Baffles. *Energy Conversion and Management*, 47 (15–16), pp. 2011–2019.

[31] Sahel, D., Ameur, H., Redouane, B., Kamla. Y., 2016. Enhancement of heat transfer in a rectangular channel with perforated baffles. *Applied Thermal Engineering*, 101, pp. 156–164.

[32] Promvonge, P., Sripattanapipat, S., Kwankaomeng, S., 2010. Laminar periodic flow and heat transfer in square channel with 45° Inline baffles on two opposite walls. *International Journal of Thermal Sciences*, 49(6), pp. 963–975.

[33] Kwankaomeng, S., Jedsadaratanachai, W., Promvonge, P., 2010. Laminar periodic flow and heat transfer in square channel with 30° inclined baffles. *Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies, Thailand*.

[34] Ripattanapipat, S., Promvonge, P., 2009. Numerical analysis of laminar heat transfer in a channel with diamond-shaped baffles. *International Communications in Heat and Mass Transfer*, 36(1), pp. 32–38.

[35] Promvonge, P., Jedsadaratanachai, W., Kwankaomeng, S., 2010. Numerical study of laminar flow and heat transfer in square channel with 30° inline angled baffle turbulators. *Applied Thermal Engineering*, 30(11–12), pp. 1292–1303.

[36] Kamali, R., Binesh, A.R., 2008. The importance of rib shape effects on the local heat transfer and flow friction characteristics of square ducts with ribbed internal surfaces. *International*

Communications in Heat and Mass Transfer, 35(8), pp. 1032–1040.

[37] Kumar, A., Kim, M.H., 2016. Heat transfer and fluid flow characteristics in air duct with various V-pattern rib roughness on the heated plate: a comparative study. *Energy*, 103, pp. 75–85.

[38] Fawaz, H.E., Badawy, M.T.S., AbdRabbo, M.F., Elfeky, A., 2018. Numerical investigation of fully developed periodic turbulent flow in a square channel fitted with 45° in-line V-baffle turbulators pointing upstream. *Alexandria Engineering Journal*, 57(2), pp. 633-642.

[39] Ismael, M.A., 2019. Forced convection in partially compliant channel with two alternated baffles. *International Journal of Heat and Mass Transfer*, 142, p.118455.

[40] Aw Lin, C., MohdSaat, F. AL-Z, Anuar, FS., Sukri, M.F., Acop, M.Z., Manan, Z.A., 2021. Heat Transfer Across Tube Banks with a Passive Control Vortex Generator in Steady One-Directional and Oscillatory Flows. *CFD Letters*, 13(1), pp. 1-18.

[41] Al-Juhaishi, L.F.M., Ali, M.F.M., Mohammed, H.H., 2020. Numerical Study in Heat Transfer Enhancement in a Curved Channel with Baffles. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 68 (2), pp. 72-83.

[42] Phu, N.M., Thao, P.B., 2021. Thermohydraulic Performance of a Fin and Inclined Flat Tube Heat Exchanger: A Numerical Analysis. *CFD Letters*, 13(7), pp. 1-12.

[43] Boonloi, A., Jedsadaratanachai, W., 2016. Numerical investigation on turbulent forced convection and heat transfer characteristic in a square channel with discrete combined V-baffle and V-orifice. *Case Studies in Thermal Engineering*, 8, pp. 226-235.

[44] Boonloi, A., Jedsadaratanachai, W., 2022. 3D-numerical predictions of flow structure and heat transfer behavior in heat exchanger tubes inserted with different patterns of double-V baffles. *Case Studies in Thermal Engineering*, 39, p.102385.

[45] Boonloi, A., Jedsadaratanachai, W., 2022. CFD analysis on heat transfer characteristics and fluid flow structure in a square duct with modified wavy baffles. *Case Studies in Thermal Engineering,* 29, p. 101660.

[46] Saha, S., Biswas, P., Narayan Das, A., 2022. Numerical Study of Turbulent Airflow Structure and Transfer of Heat Having Trapezoidal Baffles Attached on the Walls and Centerline of the Rectangular Channel. *International Journal of Applied and Computational Mathematics*, 8, 104.

[47] Cyriac, B., Bhusnoor, S.S., 2024. Numerical Studies on the Effect of Different Obstruction Geometries on Performance of Rectangular Channel Air Heaters. *Journal of Heat and Mass Transfer Research,* 11(21), pp. 43 – 52.

[48] Lazim, A.A., D.T., Ismael M.A., 2024. Cooling of lithium-ion battery pack using different configurations of flexible baffled channels. *Heat Transfer*, 53(3), pp. 1267–1291.

[49] Berner, C., Durst, F., McEligot, D.M., 1984. Flow Around Baffles. *Journal of Heat and Mass Transfer,* 106(4), pp. 743–749.

[50] Habib, M.A., Mobarak, A.M., Sallak, M.A., Abdel Hadi, E.A., Affify, R.I., 1994. Experimental Investigation of Heat Transfer and Flow Over Baffles of Different Heights. *Journal of Heat and Mass Transfer*, 116, pp. 363-368.

[51] Ko, K.H., Anand, N.K., 2003. Use of Porous Baffles to Enhance Heat Transfer in a Rectangular Channel. *International Journal of Heat and Mass Transfer*, 46(22), pp. 4191–4199.

[52] Dutta, P., Dutta, S., 1998. Effects of Baffle Size, Perforation and Orientation on Internal Heat Transfer Enhancement. *International Journal of Heat and Mass Transfer*, 41(19), pp. 3005–3013.

[53] Dutta, P., Hossain, A., 2005. Internal Cooling Augmentation in Rectangular Channel Using Two Inclined Baffles. *International Journal of Heat and Fluid Flow*, 26(2), pp. 223–232.

[54] Sriromreun, P., Thianpong, C., Promvonge, P., 2012. Experimental and numerical study on heat transfer enhancement in a channel with Z-shaped baffles. *International Communications in Heat and Mass Transfer*, 39(7), pp. 945-952.

[55] Nanan, K., Thianpong, C., Pimsarn, M., Chuwattanakul, V., Eiamsa-ard, S., 2017. Flow and thermal mechanisms in a heat exchanger tube inserted with twisted cross-baffle turbulators. *Applied Thermal Engineering*, 114, pp. 130-147.

[56] Kumar, A., Kumar, R., Maithani, R., Chauhan, R., Kumar, S., Nadda, R., 2017. An experimental study of heat transfer enhancement in an air channel with broken multi type V-baffles. *Heat and Mass Transfer*, 53, pp. 3593-3612.

[57] El Habet, M.A., Ahmed, S.A., Saleh, M.A., 2021. Thermal/hydraulic characteristics of a rectangular channel with inline/staggered perforated baffles. *International Communications in Heat and Mass Transfer*, 128, p.105591.

[58] Kurian, S., Tide, P.S., Biju, N., 2021. Effect of Baffle Configuration on Heat Transfer and Pressure Drop Characteristics of Jet Impingement System with Cross-Flow. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 86(2), pp. 15-27.

[59] Eiamsa-ard, S., Phila, A., Thianpong, C., Chuwattanakul, V., Maruyama, N., Hirota, M., 2023. Enhanced heat transfer performance in channel with delta-wing perforated V-type baffles. *Journal of thermal Analysis and Calorimetry*, 148, pp. 11283-11301.