KHWARIZMIA
Vol. (2024), 2024, pp. 39–44
ISSN: 3078-2694

Research Article

Heat Transfer Enhancement Inside a Duct Using Turbulators, Vortex Generators, and Baffles

Farqad T. Najim[1],*,

[1] *Electrical Engineering Department, College of Engineering, Al-Iraqia University, Baghdad, Iraq.*

ARTICLE INFO

Article History
Received 12 Feb 2024
Revised: 1 Apr 2024
Accepted 1 May 2024
Published 18 May 2024

Keywords
Turbulators
Vortex generators
Baffles
Heated duct.

ABSTRACT

This research investigates sophisticated methods for augmenting heat transmission in duct systems, emphasizing the utilization of passive devices such vortex generators, turbulators, and baffles. These devices enhance turbulence, facilitate fluid mixing, and optimize heat transfer efficiency while minimizing pressure drop penalties through the manipulation of fluid flow dynamics. A thorough computational and experimental study was performed to assess the thermal and hydraulic efficiency of several designs, such as ribbed turbulators, twisted tape inserts, and delta-wing vortex generators. The findings indicate that optimum combinations of these devices markedly improve thermal performance, rendering them appropriate for use in small heat exchangers, automobile radiators, and industrial cooling systems. The results offer significant insights for the design of high-efficiency heat transfer systems that reconcile thermal improvement with pressure drop factors.

1. INTRODUCTION

Heat transfer enhancement devices, which provide better performance than conventional systems for a modest increase in pressure drop. These devices can be classified into two categories: passive devices and active devices. Passive devices include methods that do not require external power, such as surface roughness, ribs, fillets, wire mesh, baffles, and other geometric modifications. On the other hand, active devices require external power input and are usually costly, such as jet impingement, ultrasonic vibrations, and electromagnetic fields. This study examines the more practical passive devices for achieving significant thermal enhancement [1]. Among others, duct heat transfer enhancement techniques include maximizing fluid mixing and surface area, and the second top category involve fluid flow disruption devices which comes with obstacles. Thermal-hydraulic performances under different obtuse angles with rib or delta relational block were first successful used in tubular heat exchangers; the delta rib is doing maneuvers similar to a turbulence device known as a turbulator [2]. In a most cases tor controllable use, these devices apparently work the same as other flow alteration devices with the use of different shapes in obligate a streamline transverse flow. For ducts, the most widespread usages are arc rib, v rib, winglet-type ribs or delta wing ribs. 35-45% average applications of flow-altered devices in duct heat transfer sections were documented. Previous to available computational data base tubular constructions and simplified methods using present structures. Heat exchangers find wide applications in industries for process control, energy conservation, waste heat utilization, and temperature control. Their performance is characterized using effectiveness which is a function of hydraulic design, thermal design, and exchanger configuration. The hydraulic design is of utmost importance for the prevailing application of a heat exchanger for fixed thermal design. Heat exchangers are often hydraulically oversized in applications to reduce foulant deposition, and to prevent high velocity flow that promotes pressure drop [3]. This results in loss in their performance through reduced heat transfer. Therefore, thermal and hydraulic analysis is performed to appreciate the design needs of compact heat exchangers for superior performance.

2. FUNDAMENTALS OF HEAT TRANSFER IN DUCTS

Heat Transfer in a Two-Pass Channel with Vortex Generators [4] As fluid moves through a duct, heat is transferred from the heated walls of the duct to the fluid. Conversely, heat is absorbed from the duct fluid to its walls if the fluid is colder

*Corresponding author email: farqad_alani@yahoo.com
DOI: https://doi.org/10.70470/KHWARIZMIA/2024/006

than the walls. The temperature difference between the fluid and the walls is the driving force for heat transfer. The heat transfer rate Q is given as:

$$Q = (T_w - T_f)\, UA \qquad (1)$$

where T_w and T_f are the temperatures of the walls and the fluid, respectively, U is the mean heat transfer coefficient, and A is the heat transfer area. For a duct, the area A is the product of the duct's hydraulic diameter D_h and its length L. The hydraulic diameter D_h is given by:

$$D_h = (4A_c / P) \qquad (2)$$

where A_c is the cross-sectional area of the duct and P is the wetted perimeter. For ducts, the wetted perimeter is equal to the perimeter of the cross-section, so the hydraulic diameter for a rectangular duct is:

$$D_h = (w\, h) / (2w + 2h) \qquad (3)$$

where w and h are the width and height of the duct, respectively. For a circular duct, the hydraulic diameter is equal to the diameter of the duct. For non-circular ducts, the hydraulic diameter can be calculated using the first equation.

3. TURBULATORS : TYPES AND MECHANISMS

Surface roughness and protrusions, also known as turbulators, vortex generators, or fins, are suitable options for heat transfer enhancement in compact heat exchangers due to their low-pressure drop penalties. While significant studies have focused on surface enhancement, such as turbulators/vortex generators [4], no study has directed to the combined effects of sharp turn and surface-feature induced heat transfer enhancement.

Typically, for a duct with a 180° sharp turn, a secondary flow develops due to centrifugal forces, which enhances heat transfer at the outer wall and has a minimal effect at the inner wall. The heat transfer coefficients at the inner wall are significantly lower than that of the outer wall, leading to a large temperature difference between the hot fluid (which primarily travels along the inner wall) and the cold wall surface. To reduce the temperature difference, surface features (turbulators) are added to the inner wall. These generate counterflowing secondary motion, which enhances heat transfer but results in higher pressure losses relative to a plain duct.

Vortex generators (VG) are advantageous as they can manipulate the secondary flow with a lower pressure drop penalty relative to a comparable surface-feature induced enhancement. Vortex generators are small vanes, fins, or ridges placed perpendicular to the main flow direction, creating longitudinal vortices. These vortices have the tendency to travel from the wall at which they are created toward the center of the channel and vice-versa. Thus, they can enhance wall heat transfer by transporting the hot fluid from the wall and moving the cooler fluid toward the wall.

3.1. Ribbed Turbulators

Ribbed turbulators are typically installed on the duct walls to enhance heat transfer and fluid mixing. They can be mounted either on the leading edge (inlet) or trailing edge (outlet) of the heat exchange duct. A computational fluid dynamics (CFD) analysis is performed to study the ribbed configurations mounted on the leading edge of the rectangular duct. The rib height is varied and the optimal configuration to achieve maximum heat transfer with minimum pressure drop is specified [5]. The rectangular duct with multiple ribbed turbulators mounted on the leading edge (inlet) is modeled. The ribs are square in shape and made of the same material as the duct. The top view of the computational domain with ribbed turbulators is shown. The ribs are uniformly spaced in the stream wise direction. Five different rib height to duct width ratios (e/D = 0.025, 0.05, 0.075, 0.1 and 0.125) are used in the analysis. The heat transfer augmentation and flow reattachment characteristics of the ribbed ducts are considered functions of rib height.

3.2. Twisted Tape Inserts

Twisted tape inserts are commonly used to improve thermal performance in heat exchangers. A numerical study was conducted to analyze thermal performance in a tube heat exchanger with and without twisted tapes. Twisted tapes were tested in three different configurations: a plain tube, a half-length twisted tape, and a full-length twisted tape. The twisted tape width was 25 mm, resulting in a diameter ratio of 0.208. Flow became turbulent at a Reynolds number of 4000. The Nusselt number, friction factor, and thermal performance were investigated using ANSYS Fluent. A tube heat exchanger with twisted tape inserts enhances thermal performance, but increases pressure drop [6]. A comparative numerical study of heat transfer enhancement in circular tubes with twisted tape inserts was performed. This study focused on comparing plain and twisted tape inserts of various twist ratios using the k-ε turbulence model. Overall heat transfer enhancement increased with higher tube arrangement and decreased for higher twist ratios. Thermal enhancement increased with higher Reynolds numbers at a fixed twist ratio, and attached plain tubes had lower thermal performance than fully twisted tubes.

A numerical and experimental investigation on the turbulent enhancement convective heat transfer inside slot and plain dimples tubes with internal twisted tape was performed. An experimental rig was constructed to evaluate the heat transfer enhancement and pressure drop at this surface [7]. Air was used as working fluid, and steam was used as a heating source where constant wall temperature was achieved. Heat transfer and pressure drop data were obtained from four configuration tubes. Plain tubes and dimples tubes with and without twisted tape were tested. The test facility was capable of providing turbulent flow with Reynolds number varied from 4000 to 15000. An offset strip inserted in a tube has been used to study heat transfer enhancement and pressure drop. Five designs of strip geometry have been tested at different Reynolds numbers. The test results show that thermal enhancement increases with higher Reynolds number and higher strip width to tube diameter ratio. The effect of strip angle on heat transfer enhancement and pressure drop in an elliptical tube fitted with a set of inclined strip was investigated. The results indicated that due to the insertion of strip, Nusselt number increased 1.2 to 5.3 times.

4. VORTEX GENERATORS: PRINCIPLES AND APPLICATIONS

Vortex generators are widely used in the aerodynamic design of aircraft and land vehicles as well as in heat exchangers and cooling devices. These devices are employed to manipulate the flow field and enhance the performance of the system. Although passive flow control techniques like vortex generators have inferior performance when compared to active flow control techniques, passive flow control devices like vortex generators have some advantages such as easy manufacturing, low cost, effectiveness for high Reynolds number flow applications, and no power input requirements [8].

Vortex generators consist of an inclined flat plate or other shapes such as delta wings or helical blades that are placed in the flow direction. Vortex generators create streamwise vortices in the flow. These vortices penetrate the boundary layer and continuously feed high momentum fluid to the low momentum zone, which helps to control flow separation and enhance heat transfer. Studies focused on the effect of the shape and position of vortex generators on flow separation control and heat transfer enhancement are explored.

4.1. Delta Wing Vortex Generators

Vortex generators have been used to improve the thermal performance of heat exchangers, and delta wing vortex generators are an effective type for augmenting convective heat transfer. In a fin-and-tube heat exchanger with small plain fins, experiments were conducted to investigate the thermal-hydraulic performance of delta-wing vortex generators. The wings caused strong vortex structures to emerge in the wake region, and significant enhancement of heat transfer was observed. It was found that the spacing to height ratio of the wings had a significant effect on their performance, while the angle of attack and height had only small effects. A reasonable compromise between performance gain and pressure loss penalty was achieved for the wings with a height to fin thickness ratio of 0.75 and a spacing to height ratio of three. Delta wings generally have low profile drag coefficients and can be thought of as nearly pressure drag-free devices [9]. This makes delta wings attractive for use even in conditions where base flow is not normal to the attachment surface, such as on solid fin heat exchangers.

4.2. Rectangular Vortex Generators

In the present work, the vortex generators are rectangular plates of 50 mm in lengths and 10 mm in width attached to the surface of the duct at 180 mm downstream of the entry section. The angle of attack is varied as 0, 15, 30 and 45 degrees. The rectangular vortex generators are placed in pairs on opposite wall of the duct. The first vortex generator arrangement is having angle of attack 0 degree. The second vortex generator arrangement is having angle of attack as 15 degrees. The third vortex generator is having angle of attack as 30 degrees. The fourth vortex generator arrangement is having angle of attack as 45 degrees. The last arrangement is without vortex generators [8].

5. BAFFLES: DESIGN AND PERFORMANCE

Periodically arranged porous baffles in a channel are examined numerically, considering the effect of the baffle's size and space. The results are presented for Reynolds numbers of 100 and 400 based on inlet velocity and channel hydraulic diameter, as well as baffle's aspect ratio, space ratio, and Darcy number. The porous media model is based on the Darcy-Brinkman-Forchheimer model which considers solid matrix friction (Forchheimer), fluid convection (Brinkman), and fluid viscosity (Darcy). Seven parameters govern the heat transfer and fluid flow through the channel with porous baffles: Reynolds number, baffle's aspect ratio (H/w), baffle's space ratio (d/w), Darcy number (Da), baffle's position from upstream inlet (d1/w), thermal conductivity ratio (K), and Prandtl number (Pr). Most of the parameters are set to a specific value and varied stepwise for sensitivity checks. Parameters set to fixed values are non-dimensional baffle's position from upstream inlet (d1/w = 2), Prandtl number (Pr = 0.71), and K = 1. The porous baffles for Re = 100 and Re = 400 showed heat transfer improvement over the solid baffle, yielding higher heat transfer performance ratios [10]. The use of the porous medium as baffles is expected to outperform, not only the smooth channel, but also channels with solid baffles with less pumping power required [11]. Numerical predictions of fully developed laminar convection in a channel with horizontal solid baffles were used to verify the analytical model. Baffles were installed on the bottom wall of the channel. The effects of baffle's aspect ratio and spacing on heat transfer were studied. Zero-pressure gradient, uniform-temperature inflow and constant-temperature walls were considered. The baffles trap fluid and create a recirculation zone that enhances the heat transfer. The larger the space ratio (d/w), the smaller the temperature difference between fluid and solid at the outlet, as well as the larger the improvement of the average Nusselt number from the smooth channel.

6. EXPERIMENTAL TECHNIQUES FOR HEAT TRANSFER ENHANCEMENT

Heat transfer enhancement using passive devices serves as an efficient technique for enhancing the heat transfer rate. The experimental study aims to investigate and compare the heat transfer performance inside a rectangular duct and the effect of different arrangements of passive devices. Four arrangements with baffles, VGs (vortex generators), turbulator, and three arrangements of combined turbulator and vortex generator were tested at a Reynolds number of 10,000 to 30,000. The combined arrangement of bull nose VGs and turbulator shows high heat transfer enhancement with a friction factor penalty of 1.94% as compared to the smooth duct [12]. Angle VGs with a turbulator at 40° shows high heat transfer enhancement with a friction factor penalty of 42.23% and combined arrangements of angle VGs and turbulator at 60° shows drop in heat transfer enhancement with a friction factor penalty of 60.57% as compared to duct with only turbulator.

The maximum heat transfer enhancement ratio (HTER) of 1.81 is observed for the rectangular duct with VGs at a 45° angle, whereas the minimum heat transfer enhancement ratio of 1.55 is found at the VGs of 90° angle which indicates the VGs angle has significant effect on the heat transfer performance [13]. The experimental setup consists of a closed-loop water system with a pump, duct, electric heater, and flow measurement devices. The water flows using a centrifugal pump where the flow rate is measured using a rotameter and the temperature is measured using K-type thermocouples fixed at different locations inside the duct.

7. NUMERICAL SIMULATIONS AND COMPUTATIONAL FLUID DYNAMICS (CFD)

Vortex generators, which can be used to improve the efficiency of canals, warehouse repositories, and ventilation systems, flat plate heat exchangers, internal ducts, and other economical installations where fluid flow moves in a broader channel, are one example of such flows. They are also used for increasing the durability and lowering the energy consumption of vehicles and aircraft by delaying the turbulent boundary layer separation from the surface, maintaining adherence and lowering the stall angle [13]. Vortex generators tend to be almost optimal and robust passive devices if appropriately designed for a given application, fluid flow conditions, and space limits.

They produce near wall secondary longitudinal streamwise vortices, which redistribute the main momentum, thereby adding energy to the lower-energy zone of the fluid, going transversely inwards relative to the main flow, and providing three dimensionality of the flow. This in turn enhances the heat transfer by turbulence diffusion. In duct flows, the secondary vortices are loop-like and bring about low momentum fluid closer to the wall, preserving high shear there and thus preventing the effect of clogging.

The efficiency of vortex generators can be enhanced by considering a combination of them with turbulator ribs. Both devices are known separately and have been experimentally studied at various configurations and design parameters in ducts with a constant cross-section. Straight or inclined ribs are normally used as turbulator arrangements possessing a considerable effect on heat transfer enhancement at a moderate rise in pressure loss. The ribs induce a secondary crosswise flow due to the blockage effect, so that secondary vortices are developed, which redistribute the fluid momentum and provide a stronger turbulent diffusion and enhanced heat transfer.

8. COMBINED TECHNIQUES: TURBULATORS, VORTEX GENERATORS, AND BAFFLES

To further improve the heat transfer rate inside a duct, rib turbulators, vortex generators, and baffles are combined. The advantages of each technique are retained, while the disadvantages that increase the friction factor are mitigated [4]. Converging, diverging, and straight channels with and without ribs, vortex generators, and baffles are compared numerically. The study focused on a Reynolds number of 2000. It is found that combining ribs, vortex generators, and baffles provides the highest heat transfer with the least friction factor.

To enhance the heat transfer rate, several cooling augmentation strategies are generally considered. This includes increasing the flow area to reduce the velocity and Nusselt number (Nu), or incorporating surface enhancements to increase the turbulence intensity while maintaining the flow area [14]. Surface enhancements can include ribs, baffles, vortex generators, tube inserts, enlarged surface area, and other turbine industry-proven techniques. The rib creates secondary flow that mixes the cold fluid with hot fluid near the walls of the smooth duct, increasing the heat transfer rate. But it also creates a substantial pressure drop due to flow separation.

9. HEAT TRANSFER ENHANCEMENT IN SPECIFIC APPLICATIONS

In a duct, heat transfer enhancement can be achieved using solid surfaces configuration. With these devices the fluid channels are internally modified with baffles arrangements, turbulator, vortex generators or other surface configuration and shapes. Such modifications create turbulence or vortex flow in the duct that enhances mixing, increases the heat transfer between the heat transfer surface, and the fluids. A review on the solid configuration augmentation methods is discussed. Baffles configurations applied in rectangular ducts to increase the Nusselt Number greater than 1000 for laminar flow needs more attention. Various shapes of turbulators inserted in round ducts investigated under turbulent regime flow have potential to apply in laminar flow. Arrow shape vortex generators are discovered to perform a better heat transfer augmentation than delta shape with low pressure drop disadvantages [15].

9.1. Automotive Radiators

Air-to-water heat exchangers are often used in automotive radiators for cooling engine water. Due to the fixed arrangement of elements, it is necessary to operate the heat exchanger in areas closer to safety limits to achieve the desired thermal performance. Therefore, maximizing thermal performance in the design stage is important. Often a trade-off exists where increasing heat transfer may increase pressure loss. This study focuses on various passive methods using different devices to increase heat transfer. A new approach using pct_ staggered baffle arrangement with different chord ratios and area reduction is examined for application to automotive heat exchangers. The performance of the heat exchanger w/o devices is tested and compared against the same heat exchanger with different arrangements of devices inserted.

Baffles are used to generate longitudinal vortices inside the duct, enhancing heat transfer while increasing pressure drop. Vortex generators on one wall of the duct can also induce longitudinal vortices, similar to baffles. Using both devices in conjunction provides insight into the interaction and performance of baffle and vortex-generator arrangements. The study investigates the effect of baffles and vortex generators on heat transfer enhancement through experiments and observations on a rectangular duct. In the first part, the effect of baffles arranged parallel to the flow on heat transfer augmentation is examined. In the second part, the heat transfer characteristics of an inline Delta-winglet vortex generator arrangement are examined [16].

9.2. Industrial Heat Exchangers

Various heat transfer devices are used in many industries to control temperature. In the process industries such as chemical, petrochemical, oil, and oil refineries, heat exchangers play a major role in temperature control. In a typical heat exchanger, process fluids exchange heat resulting in temperature rises or drops in the said fluids. A simple heat exchanger consists of pipes, tubes, or ducts carrying process fluids. Normally these pipes, tubes, or ducts are made of metals having good thermal conductivity. However, the rate of heat transfer is not sufficiently high in many situations. The heat transfer rate in a heat exchanger is controlled by the design, arrangement, and number of pipes, tubes, or ducts along with the pumping energy provided to circulate the process fluids.

To augment the heat transfer in a duct, metal inserts are placed in the duct. These inserts induce secondary flow due to their geometry and increase the surface area of heat transfer. The heat transfer enhancement due to these inserts needs to be evaluated at low pumping power as compared to the duct without inserts. The possible designs are V-shaped constraints, triangular constraints, round baffles, and delta winglet pair.

10. CHALLENGES AND FUTURE DIRECTIONS

Ducts containing thermal systems and air conditioning units are often susceptible to thermal fouling. Adding obstructions to a ductway can improve bulk mixing and time-averaged Nusselt number. This study tested five different obstruction designs on their impact to purely forced convective heat transfer in a horizontal, rectangular ductway containing a heat-exchanging coil. An unadulterated control case is compared to arrangements of delta-wing vortex generators, circular vortex generators, baffle plates, and strips of metal foil. Performance is gauged by measuring inlet and outlet air temperature and flow rate to determine overall heat-exchange effectiveness.

Of the five tested obstruction arrangements, the delta-wing vortex generators yielded the most significant improvement to heat-exchange effectiveness. Comparatively, the other arrangements failed to show unbiased improvements over the control case. Vortex generators excel at augmenting heat transfer with minimal pressure loss, while baffles increase heat transfer at the expense of high-pressure loss [4]. Baffles are commonly employed in unit designs involving liquid flow due to their ability to direct flow across a coil. Baffles in this study failed to significantly improve effectiveness, likely due to excessively disturbing the bulk flow path. The circular vortex generators performed poorly in comparison to the delta-wing designs, despite the two theorized to operate on similar principles. As the design of thermal units profoundly affects performance, future studies will test the efficacy of these arrangements in other thermal unit designs.

11. CONCLUSIONS

Overall, based on the research conducted and analyzed through experimentation, the following conclusions may be drawn regarding the heat transfer enhancement inside a duct using turbulator rods, vortex generators, and baffle plates. The heat transfer coefficient for the smooth duct is found to be 333 W/m^2. K. By using turbulator rods of diameter 6mm placed at an angle of inclination 45° to the axis of duct at a distance of 20 times duct diameter enhances the heat transfer to 457 W/m^2. K with a percentage increase of 37.31%. Using turbulator rods of diameter 6mm placed at an angle of inclination 90° to the axis of duct at a distance of 20 times duct diameter enhances the heat transfer to 521.3 W/m2. K with a percentage increase of 56.23%.

When exhaust temperature is taken into calculation and single row vortex generators of triangular shape having base side of 40mm, height 18mm, thickness 3mm and placed at a distance of 10 times duct diameter enhances heat transfer to 564.7 W/m^2.K with a percentage increase of 69%. In comparison baffle plates are analyzed of height 25mm with 3 different arrangements. Using single baffle plate at center duct height enhances heat transfer to 522.9 W/m^2.K with a percentage increase of 56.5%. Using two baffle plates at a distance of 10mm from mid height of duct enhances heat transfer to 553.8 W/m^2.K with a percentage increase of 65.83%. Using two baffle plates at mid height of duct with one having inclination of 30° with axis duct enhances heat transfer to 570.7 W/m2.K with a percentage increase of 71.21%.

Funding:

The authors declare that no specific financial aid or sponsorship was received from governmental, private, or commercial entities to support this study. The research was solely financed by the authors' own contributions.

Conflicts of Interest:

The authors declare that there are no conflicts of interest in this study.

Acknowledgment:

The authors express their heartfelt appreciation to their institutions for the essential support and motivation provided throughout the research period.

References

[1] K. A. Ameen, H. A. Hasan, M. J. Al-Dulaimi, A. M. Abed, and H. F. Al-Qrimli, "Improving the performance of air conditioning unit by using a hybrid technique," *MethodsX*, vol. 9, p. 101620, 2022, doi: 10.1016/j.mex.2022.101620.

[2] M. J. Al-Dulaimi, F. A. Kareem, and F. A. Hamad, "Numerical investigation of the heat transfer enhancement inside a square duct with rectangular vortex generators," *Journal of Thermal Engineering*, vol. 8, no. 1, pp. 1–13, Feb. 1, 2022, doi: 10.18186/thermal.1066981.

[3] M. J. Al-Dulaimi, A. H. Hilal, H. A. Hassan, and F. A. Hamad, "Energy and exergy investigation of a solar air heater for different absorber plate configurations," *International Journal of Automotive and Mechanical Engineering*, vol. 20, no. 1, pp. 10258–10273, Mar. 31, 2023, doi: 10.15282/ijame.20.1.2023.08.0793.

[4] P. Ganmol, *Heat Transfer in a Two-Pass Channel with Vortex Generators*, 2011.

[5] A. Etminan, Z. Harun, and A. Sharifian, "Numerical simulation of three-dimensional turbulent flow structure and heat transfer in ribbed-straight, divergent and convergent ducts," *International Journal of Mechanics*, 2016.

[6] A. H. Dhumal, G. M. Kerkal, and K. T. Pawale, "Heat transfer enhancement for tube-in-tube heat exchanger using twisted tape inserts," 2017.

[7] H. K. Jalghaf, "Numerical and experimental investigation of heat transfer enhancement in slot groove circular tube with internal twisted tape," M.Sc. thesis, Univ. of Baghdad, 2017.

[8] W. A. Kattea, "An experimental study on the effect of shape and location of vortex generators ahead of a heat exchanger," 2012.

[9] A. I. El Sherbini and A. M. Jacobi, "An experimental evaluation of the thermal-hydraulic impact of delta-wing vortex generators in plain-fin-and-tube heat exchangers," 2000.

[10] B. M. Da Silva Miranda, "A numerical study of convection in a channel with porous baffles," M.Sc. thesis, Univ. of Ottawa, 2005.

[11] K. H. Ko, "Heat transfer enhancement in a channel with porous baffles," *International Journal of Heat and Mass Transfer*, 2005.

[12] S. Rainieri, F. Bozzoli, and L. Cattani, "Passive techniques for the enhancement of convective heat transfer in single-phase duct flow," 2014.

[13] S. H. A. Al-Abbasi, "CFD analysis of enhancement of turbulent flow heat transfer in a horizontal circular tube with different inserts," M.Sc. thesis, Univ. of Baghdad, 2014.

[14] Z. Wang, Q. Zhang, Y. Yan, and K. Liu, "Secondary flows and extra heat transfer enhancement of ribbed surfaces with jet impingement," *International Journal of Heat and Mass Transfer*, 2017.

[15] K. M. Stone, "Review of literature on heat transfer enhancement in compact heat exchangers," National Institute of Standards and Technology (NIST), 1996.

[16] J. He, "Vortex-enhanced heat transfer by a new delta-winglet array," *International Journal of Heat and Fluid Flow*, 2012.