Enhancing heat transfer performance: A comprehensive review of perforated obstacles

Y. Menni[a], N. Kaid[a], M. A. Alkhafaji[b], M. Bayram[c], O. M. Ikumapayi[d] and A.J. Chamkha[e]

[a]*Energy and Environment Laboratory, Department of Mechanical Engineering, Institute of Technology, University Center Salhi Ahmed Naama (Ctr. Univ. Naama), P.O. Box 66, Naama 45000, Algeria.*
[b]*College of Technical Engineering, National University of Science and Technology, Dhi Qar, 64001, Iraq.*
[c]*Department of Computer Engineering, Biruni University, 34010, Istanbul, Turkey.*
[d]*Department of Mechanical and Mechatronics Engineering, Afe Babalola University, Ado Ekiti 360101, Nigeria.*
[e]*Faculty of Engineering, Kuwait College of Science and Technology, Doha District, 35004, Kuwait.*

Received 10 April 2024; accepted 7 December 2024

Heat exchangers (HEs) find application in a variety of industrial processing and thermal management systems in which heat transfer (HT) is generally the critical requirement for successful operation. This paper reviews the application of perforated obstacles to HT augmentation in HEs by combining recent findings of numerical simulations and experimental investigations. The numerical evaluation encompasses a detailed analysis of the various geometric parameters of the perforated obstacles, including perforation shape and size, distribution, and spacing, along with relevant operating parameters. This study well represents their deep impact on overall HE performance. Our findings convincingly indicate that the obstacles with perforations were substantially successful at improving HT rates while lowering pressure drop, which evidences itself by high HT coefficients. Further, different industrial applications of perforated obstacles have been exhibited in HVAC systems (Heating, ventilation, and air conditioning), automotive cooling and refrigeration, and in process industries, with great versatility and scalability. This review, therefore, gives insight into the possible use of perforated obstacles in the complete revolution of HT efficiency within HEs while while paving the way for further researche in thermal engineering and industrial processes.

Keywords: Heat transfer enhancement; fluid flow; heat exchangers; perforations; numerical simulations; experimental studies; pressure drop.

DOI: https://doi.org/10.31349/RevMexFis.71.030601

1. Introduction

Heat exchangers (HEs) are devices used to transfer heat (HT) across two or more fluids, or from one solid surface to a fluid at different temperatures (Rebhi *et al.* [1]). They are also used in many fields and applications: HVAC systems (Heating, ventilation, and air conditioning) (Ahmad *et al.* [2]; Djeffal *et al.* [3]; Tahrour *et al.* [4]; and Sakhri *et al.* [5-7]), chemical processing (Phillips *et al.* [8]), power generation (Orts-Gonzalez *et al.* [9]), and refrigeration (Zheng *et al.* [10]).

This HT is achieved through two ways: passive (Liu and Sakr [11]; and Sheikholeslami *et al.* [12) and active (Andrzejczyk *et al.* [13]; and Thapa *et al.* [14]). HEs exist in various forms, such as shell-and-tube (Abd *et al.* [15]; and Rashidi *et al.* [16]), plate-and-frame (Arsenyeva *et al.* [17]; and Arsenyeva *et al.* [18]), finned tube (Geiser and Kottke [19]; Bhuiyan and Islam [20]; and Basavarajappa *et al.* [21]), and compact HEs (Stone [22]; Shah [23]; and Li *et al.* [24]), each suitably applicable according to the fluid properties, operating conditions, space constraints, and other variables.

Active techniques of HT augmentation serve with the help of external energy input or mechanical systems to enhance HT rates in a system:

- This involves mechanical devices to apply turbulence on fluid flow, using pumps, mixers, or agitators among others. The turbulent flow promotes mixing and disrupts the boundary layer to increase the convective HT coefficients, hence enhancing HT as justified by Konopacki *et al.* [25]; Qi *et al.* [26]; and Maxson *et al.* [27].
- Techniques of electrohydrodynamics are those methods attempting to influence fluid flow with the help of electric fields in order to enhance HT enhancement (Molki and Damronglerd [28], Laohalertdecha *et al.* [29], and Wang *et al.* [30]). The action of electrostatic or electromagnetic forces induces fluid motion, reduces boundary layer thickness, enhancing convective HT rates, especially in the case of micro-channels and complex geometries.
- As many researchers have realized the fact that the application of acoustic or ultrasonic waves to the fluid can destroy boundary layers, thereby enhancing mixing and improving HT rates, the use of acoustic waves in improving HT has been studied by Chen *et al.* [31]; Setareh *et al.* [32]; and Zhang *et al.* [33].
- Controlled mechanical vibrations can be imposed to enhance HT due to fluid mixing and thinning of stagnant boundary layers associated with it. In this manner, vibrational enhancement becomes very effective in microchannels and low flow rate applications, as shown

by Shoele and Mittal [34]; Duan *et al.* [35]; and Fu *et al.* [36].

- Nanofluids are engineered suspensions of nanoparticles in a base fluid usually water or oil. With the high thermal conductivity of nanoparticles, the overall thermal conductivity of the fluid is augmented, hence the enhancement in the performance of HT concerned (Menni *et al.* [37-39]; Maouedj *et al.* [40]; Mahammedi *et al.* [41]; and Boursas *et al.* [42]).

- Magnetic fields may be applied to ferrofluids or paramagnetic fluids, causing fluid motion and thus enhancing convective heat transfer. Wang *et al.* [43]; Bezaatpour and Goharkhah [44]; and Zhang and Zhang [45] discuss the enhancement of convective HT by the application of magnetic fields. Fluid flow patterns could be altered by a magnetic field to enhance HT efficiency. These active methods provide an avenue to achieve a substantial increase in HT rates in several areas of application; and they can be matched to each type of performance need, as well as to operational conditions.

Passive techniques of thermal enhancement do not have any external energy input and operate on the principle of fluid dynamics combined with HT. In fact, many passive techniques require geometrical modification or specially designed material for the enhancement of the process of HT. Some of the popularly used passive techniques include:

- Special geometries or surface patterns that enhance the effective surface area and promote fluid mixing for the augmentation of convective HT: fins, dimples, grooves, and microchannels (Chamkha *et al.*, [46]; Djeffal *et al.*, [47]; Rebhi *et al.*, [48]; Hammid *et al.*, [49]; Eiamsa-ard and Promvonge, [50]; Ligrani *et al.*, [51]; and Menni *et al.*, [52]).

- The application of high thermal conductivity or low emissivity coatings to HT surfaces so as to enhance HT rates by reducing thermal resistance (Chatys and Orman [53]; and Nguyen and Ahn [54]).

- Optimization of the HE geometry by increasing the number of tube passes, improving tube layouts maximizes the HT effectiveness while minimizing pressure drop (Korti *et al.* [55]; and Youcef *et al.* [56]).

- The methodology of passive device investigation: turbulators or vortex generators (VGs) are placed in the fluid flow path with an intention to induce turbulence, aiming at enhancing convective HT (Menni *et al.* [57,58]; and Salmi *et al.* [59]).

- Using passive means, such as surface roughening or even placing baffles at strategic locations to enhance convection and, hence, HT in systems where buoyancy effects are of leading importance (Menni and Azzi [60,61]; Menni *et al.* [62-64]; Ameur *et al.* [65,66]; Chamkha and Menni [67]; Salmi *et al.* [68]; Medjahed *et al.* [69]; and Afif *et al.* [70]).

- Besides, passive methods based on magnetic fields have appeared as promising tools for efficient HT enhancement. Of special interest are heterogeneous magnetic-field-based techniques interacting with electrically conducting fluids. This interaction generates Lorentz forces, which can be utilized to destabilize the flow by altering the mean-flow velocity distribution with a corresponding augmentation of HT [71]. The use of electrically conducting fluids in these passive techniques precludes any external energy or mechanical-related systems to alter flow patterns, hence, these are promising alternatives to enhance thermal performance [72-74].

These passive methods are cost-effective and environmentally benign ways of enhancing HT in applications that range from a simple HE to electronic cooling systems with little maintenance and energy consumption.

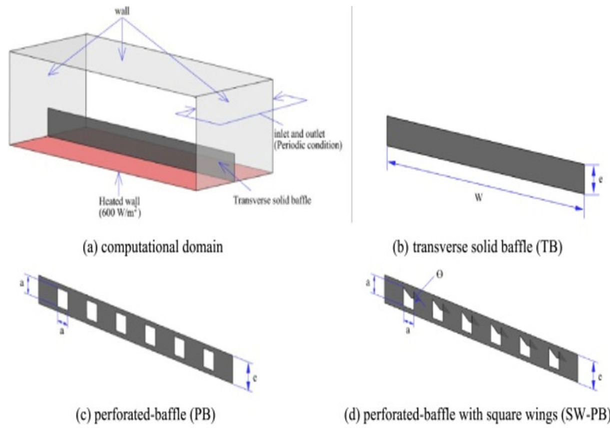
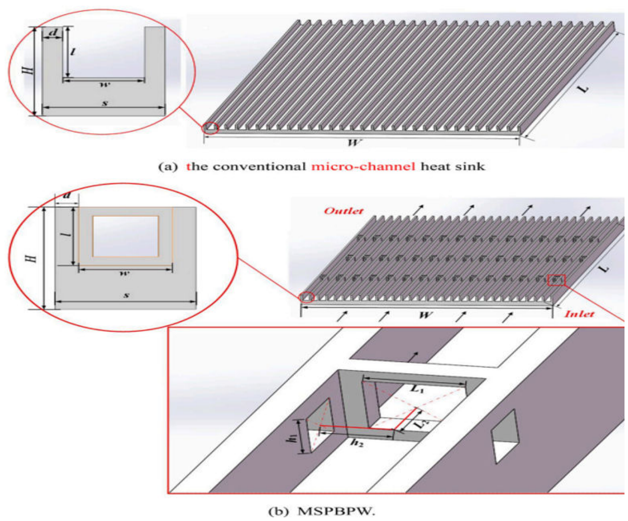
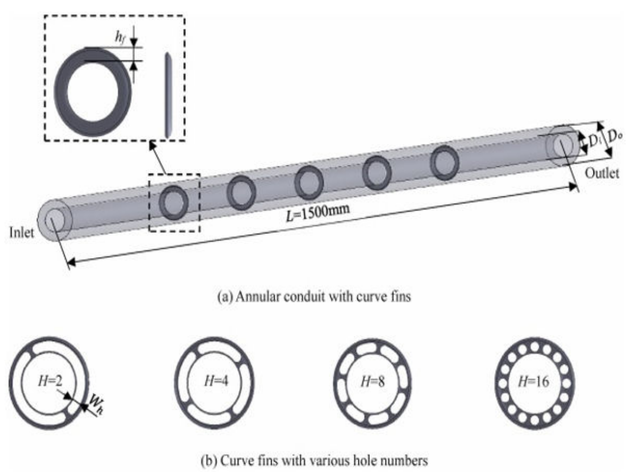
Some of the devices employed to enhance HT in various engineering applications include perforated VGs, turbulators, deflectors, baffles, fins, and ribs. Each of them works on different principles and is employed for specific requirements and conditions. They have small perforations or holes at strategic locations over obstacles or surfaces that come into direct contact with fluid flow. The perforations, when fluid flows over such surfaces, induce vortices that disturb the boundary layers and thus help in enhancing HT through mixing and a reduction in thermal resistance. Perforated obstructions are quite effective in increasing HT coefficients and hence find wide applications in HE design and cooling systems where space and efficiency are the prime factors of concern.

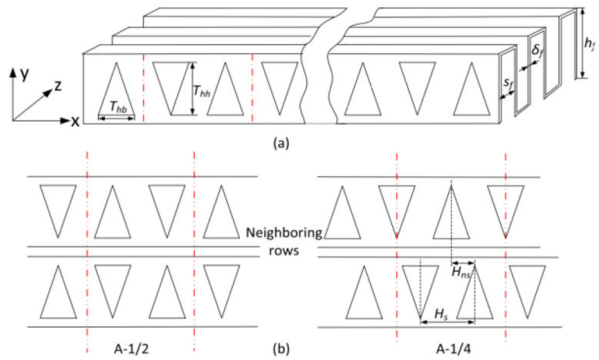
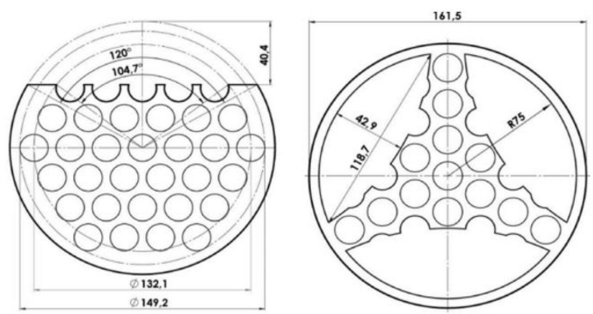
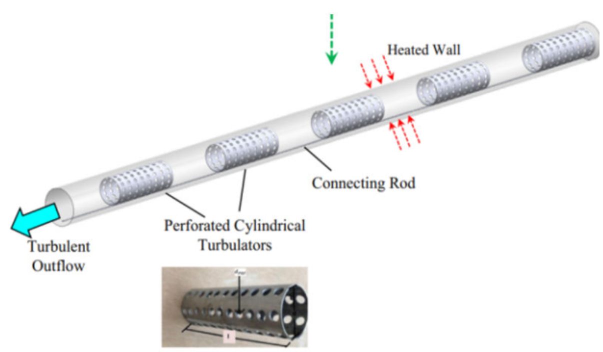
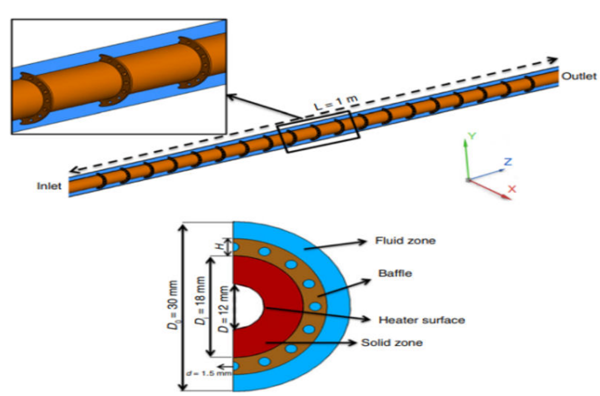
The present review analysis, therefore, tries to capture the essence of the enhancement in HT brought about by perforated obstacles in HEs using numerical simulations and experimental studies. It goes into critical analysis through various geometric dimensions of perforated obstacles along with operational parameters that can provide the effects on the performance of HEs. It also explores the vast application of perforated obstacles that ranges from HVAC systems, automotive cooling, refrigeration, and process industries showing that this method can be versatile as well as scalable. Basically, the present review aims at an in-depth understanding of how perforated obstacles can change the course of heat transfer efficiency inside HEs and thus advancements in thermal engineering and also industrial processes.

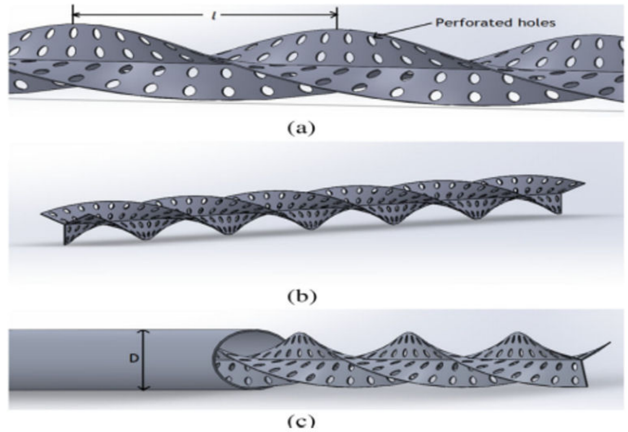
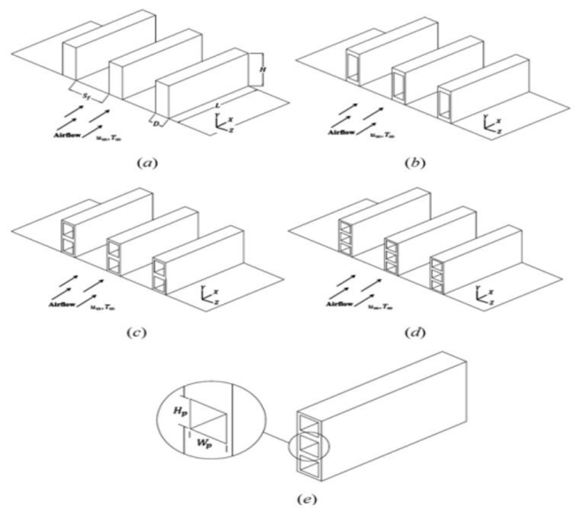
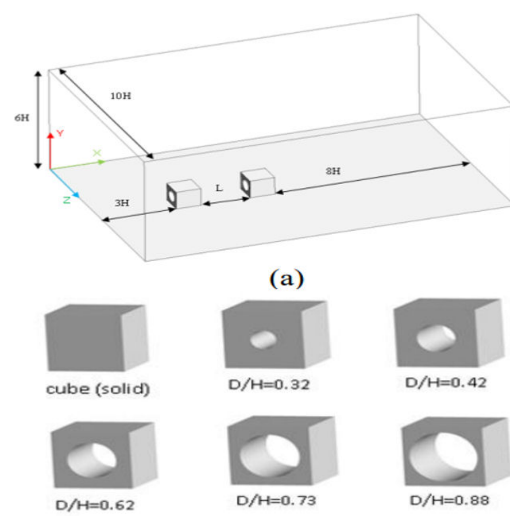
2. Assessing numerical investigations

The use of perforated obstacles represents a promising method for performance enhancement of HEs. Such obstacles are inserted into the HE system in order to disrupt bound-

TABLE I. Significant HEs analyzed through numerical simulations with perforated obstacles.

Authors	**Computational configuration**
Eiamsa-Ard *et al.* [75]	 *Perforated-baffles*
Liu *et al.* [76]	 *Perforated baffles/walls*
Wang *et al.* [83] [76]	 *Perforated curve fins*

Authors	**Computational configuration**
Li *et al.* [89]	 *Triangular perforated fin*
Biçer *et al.* [93]] [76]	 *Conventional and three-zonal baffle*
Nakhchi *et al.* [96]	 *Perforated cylindrical turbulators*
Ghanbari and Javaherdeh [103]	 *Perforated-baffles*

Authors	**Computational configuration**
Gautam *et al.* [108]	 *Perforated triple wing VGs*
Shaeri and Jen [113]	 *Three-dimensional and rectangular perforated fins*
Rostane and Abboudi [118]	 *Arrangement of cubes with perforations in tandem*

ary layers, enhance HT rates, and optimize fluid flow characteristics. A great number of different numerical studies considered performance of such configurations. For instance, the following Eiamsa-Ard *et al.* [75]; Liu *et al.* [76,77]; Tuncer *et al.* [78]; Sahel *et al.* [79]; Chamoli [80]; Chamoli and Thakur [81]; Kandukuri *et al.* [82]; Wang *et al.* [83-85]; Song *et al.* [86]; Boukhadia *et al.* [87]; Ismail *et al.* [88]; Li *et al.* [89]; Ganie *et al.* [90]; Ameur and Menni [91]; Zhao *et al.* [92]; Biçer *et al.* [93]; Pérez *et al.* [94]; Tavakoli and Soufivand [95]; Nakhchi *et al.* [96]; Javanmard and Ashrafizadeh [97]; Hedau and Saini [98]; Zou *et al.* [99]; Sun *et al.* [100]; Dastbelaraki *et al.* [101]; Razavi *et al.* [102]; Ghanbari and Javaherdeh [103]; Xue *et al.* [104]; Qi and Yuan [105]; Godi [106]; Godi and Petinrin [107]; Gautam *et al.* [108]; Van Hap *et al.* [109]; Lertnuwat [110]; Esmaeili and Rashidi [111]; Jain *et al.* [112]; Shaeri and Jen [113]; Shaeri and Yaghoubi [114,115]; Huang *et al.* [116]; Barzoki *et al.* [117]; and Rostane and Abboudi [118] are thus capable of adding meaningful insights. On the other hand, Table 1 summarizes some of the key works that are deemed necessary to be taken into consideration for a fully informed state-of-the-art overview.

Eiamsa-ard *et al.* [75] performed the HT performance of a square wings case (SW-PB) using the modified perforation-baffle configuration in a channel. Unlike the classical transversal solid baffle (TB), impinging jets and recirculation flows were produced. In contrast, the perforated baffle yielded smaller recirculation but lower HT rates compared to TB and SW-PB, resulting in the reduction of friction losses. In this direction, Liu *et al.* [76] proposed a new microchannel heat sink with perforated baffles/walls, MSPBPW, which was proposed to enhance the temperature of the heating sink lower surface distribution. They numerically investigated two parameters: L_1, the width of the rectangular hole on the baffle, while L_2 represents the distance from the channel wall perforation to the baffle hole center. Their observations revealed that this geometry greatly improved the performance of HT despite the resultant pressure drop. Further, both the Nu number and the f coefficient reduced with L_1 improvement and increased upon rising L_2.

Liu *et al.* [77] investigated the enhancement of perforated ribs in a cooling channel with added inclined holes. They showed that for larger inclined angles, the averaged Nusselt (Nu) in the inclined scenarios was higher than that for the straight ones due to the fact that flows were directed toward the incline. Tuncer *et al.* [78] enhanced a solar drying system with an advanced improved absorber coating with ZnO nanoparticles and an infrared heating system; it was also concluded that vertical solar heater cases with perforated baffles presented optimum performance.

On the other hand, Sahel *et al.* [79] conducted a computational performance evaluation of a new baffle geometry inside the channel and reported that there was a remarkable enhancement of HT for the perforated baffle rather than the plain baffle geometry. Chamoli [80] explored the effects of V-downward-facing perforated baffle-roughened channels on HT and friction loss, and the optimal geometric parameters obtained by using Response Surface Methodology (RSM) and artificial neural network (ANN). Further, Chamoli and Thakur [81], by using the exergy method, estimated the exergetic efficiency of these ducts in a solar air heater (SAH) and showed an improved heat absorption and dissipating capability over conventional systems, and hence developed design plots to predict optimum roughness parameters. The research proposed by Kandukuri *et al.* [82] related to the two varieties of the distributive mode active solar dryers and the dynamic response of the phase change material (PCM) in both melting and solidification phases. Numerical investigations were conducted for finned annular passages with different geometries and perforation numbers using nanofluid by Wang *et al.* [83], and they suggested a curved fin passage with eight perforations for the maximum value of the HT coefficient.

Numerical investigations by Wang *et al.* [84] focused on the influence of implementing a perforated helical tube disrupter on thermal and exergetic performance of a solar-thermal photovoltaic hybrid system and demonstrated better performance with the perforated turbulator configuration compared to non-perforated and no turbulator configurations, and a boosted regression tree-BRT-ensemble machine learning model was developed for the efficiency prediction. Furthermore, an investigation concerning different shapes and situations of VGs on a dual-tube HE was carried out by Wang *et al.* [85] and some views were presented which are of great importance for their optimization design with the purpose of enhancing the efficiency of a system.

Song *et al.* [86] proposed a new HE with an annular region perforated helical fin and presented the significant enhancement in its thermal performance: for example, the maximum Nu value increased by 20.2% and was recommended for optimization studies in double-tube HE designs. Moreover, Boukhadia *et al.* [87] conducted three-dimensional numerical studies to investigate the performance of VGs in a plate fin HE. Rectangular and perforated wings were utilized as the VGs to enhance the HT rates within this study. In addition, new correlations have been developed to predict the friction factor (f) and Nusselt number (Nu) based on Reynolds number (Re) and on the shape of the perforations in baffles. Ismail *et al.* [88], in turn, investigated the solid and perforated fin array installed on a flat surface on the influences of HT enhancement and friction loss, finding that the arrangement of circular perforation increased the enhancement of HT and decreased friction loss. On the other hand, Li *et al.* [89] proposed a unique triangular perforated design for fins; the authors conducted a numerical simulation to see its convective HT behavior and found that it offered superior performance over serrated fins through analyzing the Colburn factor, friction factor, and field synergy principle. Meanwhile, Ganie *et al.* [90] investigated the thermal field of fluid flow in a duct with a perforated barrier by computational simulations. The investigations have been performed regarding the temperature-velocity variations across different angles of the plate; the linear increases of HT were pointed out and the optimal angles which assure an optimum in the velocity field and downstream temperature together with friction factor and pressure distribution were underlined.

Ameur and Menni [91] introduced circular perforations in the baffle structure of a HE to reduce friction losses, and substantial improvements in HT for different perforation configurations and Re numbers were reported. On the other hand, a mathematical model was developed by Zhao *et al.* [92] which analyzed the effect of inserting a perforated plate on the operational efficiency of the exhaust thermoelectric generator. It showed that an optimal positioning of the plate could eventually realize an increase in output power by as much as 73.4% and improvement in the voltage evenness coefficients with no significant effect that may be caused by the mass flow rate and temperature variations. Along the same direction, Biçer *et al.* [93] have proposed a new baffle geometry to decrease the pressure drop through the shell side of shell-and-tube THs without compromising thermal performance. The three-zonal superior baffle geometry was identified by the CFD analysis which attained 49% reduction in shell side pressure loss and slight enhancement in thermal performance.

Pérez *et al.* [94] carried out a numerical study on the effect of a delta winglet pair of perforated VGs on thermohydraulic performance of a channel for different geometries and configurations. The model was validated through comparison with correlations available in the literature. Another work, Tavakoli and Soufivand [95], performed the numerical analysis of a parabolic solar collector using a hybrid nanofluid of water, Al_2O_3, and MWCNT. They have investigated twisted tape turbulators that are finned and perforated, and their conclusion was that the use of perforated tape gave better HT and overall performance improvement. Proceeding further, Nakhchi *et al.* [96] attempted to study HT in double-pipe HEs with turbulent nanofluids and turbulators of perforated cylindrical geometry. They found that the new proposed model remarkably augment the thermal performance up to 1.931 in terms of factor of thermal performance. Javanmard and Ashrafizadeh [97] studied a set of perforated ribs. They found that the Case #212 rib significantly enhanced performance. The hole inclination angle played a key role in this enhancement.

Hedau and Saini [98] conducted a computational study of a double pass SAH. The author's introduced transversely disposed semi-circular tubes along with rectangular perforated blocks to introduce artificial roughness. They found that the optimum thermo hydraulic performance would occur for a particular open area ratio and reduced relative blockage-height ratio. Zou *et al.* [99] discussed the use of perforated-serrated fins in cryogenic helium systems. They reported a better HT performance for these fins compared to conventional serrated ones for low Re numbers. Such geometrical changes can be adopted in designing plate-fin HEs below 80K. Sun *et al.* [100] carried out a numerical study on parameters that influence the cooling effectiveness of perforated flat plates. They have proposed a new optimization technique that will help in giving a better performance in transpiration cooling with less coolant consumption, using a nonuniform allocation strategy.

Meanwhile, other researchers, such as Dastbelaraki *et al.* [101], studied the thermal performance of perforated fins in comparison to solid fins and surfaces without fins, concluding that three-opening configurations exhibited better thermo-hydraulic performance. Razavi *et al.* [102] numerically performed an evaluation of the effect of inclined baffles with perforations in a channel under laminar conditions. It was found that such baffles improved Nu and reduced f over solid baffles. An optimal angle of 135° gave the best HT with a minimum of friction. In another work, Ghanbari and Javaherdeh [103] studied the hydrodynamic convection and variation in pressure of a non-Newtonian fluid flow within a heated annulus tube. They also obtained that the addition of nanoporous graphene to the base fluid increased the average Nu up to 32% and increased pressure drop up to 75%. They also estimated that for annular tubes having specific baffle configurations, the addition of nanoporous graphene increased the system efficiency by up to 11.9%.

In another field, the work of Xue *et al.* [104] presented liquid sloshing in a rectangular tank with perforated baffles. They did analysis on the free surface fluctuation as well as the pressure distribution for a variety of excitation frequencies, and good comparisons among experimental and computational results and spectral analysis for free surface elevation were obtained. Qi and Yuan [105] conducted an investigation into the performance of multi-layered porous covers for discrete solid block cooling inside a 2D duct. Of the different configurations tested, the two most superior configurations involved those that had maximum permeability in all layers (Case A) and a configuration where the permeability decreased towards the outside (Case D). Godi [106] conducted a numerical analysis for micro-channels fitted with fins for both solid and perforated configurations, and while searching for global thermal conductance maximization, had also showed that for 20% increase in Re number of coolant minimum temperatures were reduced. Godi and Petinrin [107] conducted a 3-D numerical optimization study on fin geometries, solid and perforated, in a cooling system.

Besides, Gautam *et al.* [108] tested, in circular tube HEs at various Re numbers, the enhancement of HT by using a perforated triple-wing VG with several twist ratios and porosities. Very positive enhancements in HT and overall performance were obtained when compared to arrangements that included the use of smooth tubes. Van Hap *et al.* [109] proposed hybrid turbulators using perforated circular segments as VGs in the air collector ducts. Numerically, it was presented in 3D with experimental validation that segment arrangements, angles of attack, and Re numbers have a great influence; optimal performance was recorded at the angle of attack equal to 30° and Nu number as well as friction factor in a staggers arrangement was better when compared with an in-line arrangement. Lertnuwat [110] also explored how hole positions can affect the performance of the trapezoidal winglet VG in a SAH for a duct configuration in the rectangular case.

Entropy generation in the HT process and flow of nanofluids within a 3D duct with transverse twisted VGs punctured with holes were investigated by Esmaeili and Rashidi [111]. They found that the coefficient of HT increases with an increase in the number of holes, while the pressure loss decreases. The optimal performance is obtained when the baffles have four holes and a 540-degree pitch. In another similar attempt, Jain *et al.* [112] numerically explored the thermal performance of a SAH fitted with different perforated V-shaped VGs and presented outstanding improvements in Nu number and friction coefficient. The turbulent HT characteristics of perforated fins were investigated by Shaeri and Jen [113], and their results showed that more numbers of perforations for the given value of porosity promote the HT effectively. Also, the perforated fins have much lower total drag, which is reduced with fewer perforations.

Then, Shaeri and Yaghoubi [114] investigated numerically the laminar hydrodynamics characteristics and HT over heated arrays of rectangular perforated and solid fins on a flat surface. They reported that perforated fins offer enhanced performance and weight reduction. They suggested a correlation to predict the effectiveness of perforated fins in their computed range. Further, Shaeri and Yaghoubi [115], in their numerical investigation, showed flow and HT behaviors of solid and perforated fins. The results reflected an efficient enhancement of HT and a reduction in weight in the fins with longitudinal pores compared to solid ones.

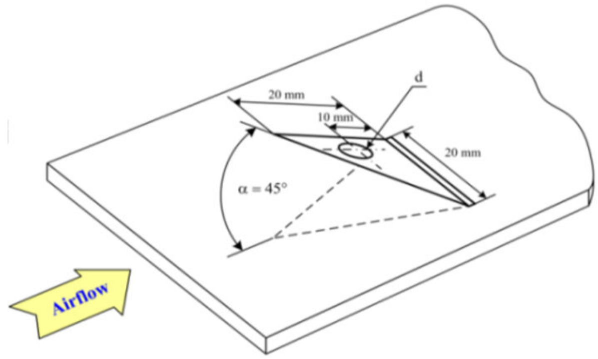
Huang *et al.* [116] proposed a new perforated baffle-based collector aiming to improve the performance of SAHs. Some desired features such as pressure loss, increased collection efficiency, and improvement of HT coefficients were observed from the CFD simulations for these collectors. Optimal dimensions of the holes and opening ratios that yield good performance have been pointed out. Barzoki *et al.* [117] performed a study of turbulent water flow through a rectangular duct with chevron plat-fin configurations punched with perforations. Different shapes of VGs were incorporated into the study, and it showed better performance indices for the models with VGs. Among them, the half-circle VG had the highest thermohydraulic efficiency, while the square and forward triangular VGs were better in their categories. While, Rostane and Abboudi [118] also reported that HT from sequential cubes, which were placed on a flat surface with holes, was enhanced for cube diameters greater than D/H = 0.62, with the enhancement increasing with the increase in the cubes' perforation diameter.

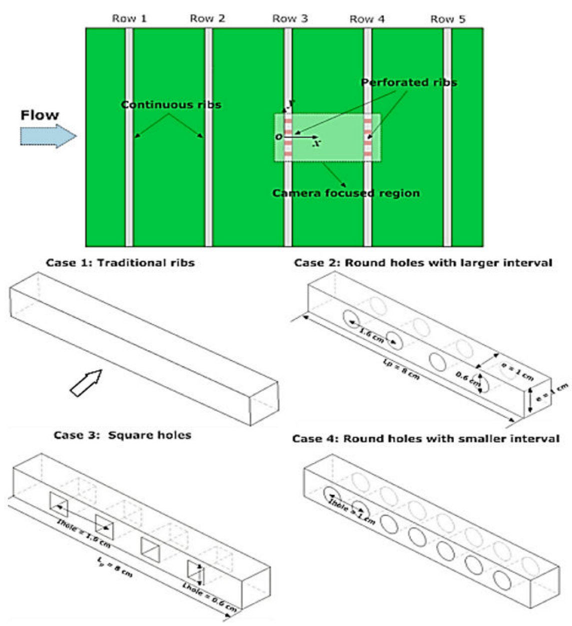
3. Assessing experimental investigations

Complementing the above numerical investigations, various experimental methods have also been explored in literature, yielding quite useful information for enhancement of HT with perforated obstacles. Significant contributions by El Habet *et al.* [119]; Skullong *et al.* [120]; Khanlari *et al.* [121]; Liu *et al.* [122]; Varol *et al.* [123]; Vaisi *et al.* [124]; Chin *et al.* [125]; Awasarmol *et al.* [126]; Tandel and Modi [127]; Chamoli [128] ; Chamoli and Thakur [129]; Chang *et al.* [130]; Ghanbari *et al.* [131]; Salem *et al.* [132]; Khoshvaght-Aliabadi *et al.* [133, 134]; Pankaj *et al.* [135]; Hassan *et al.* [136]; Pandey and Kumar [137]; Saravanan *et al.* [138]; Karabacak and Yakar [139]; Promvonge *et al.* [140]; Khargotra *et al.* [141, 142]; Huang and Liu [143]; El Habet *et al.* [144]; Molki and Hashemi-Esfahanian [145]; Singh *et al.* [146,147]; Nakhchi *et al.* [148]; Fan *et al.* [149]; Sheikholeslami and Ganji [150]; Buchlin [151]; Nuntadusit *et al.* [152]; Sara *et al.* [153]; Eiamsa-Ard *et al.* [154,155]; Bhattacharyya *et al.* [156]; Gel'Fand *et al.* [157]; and Rahman [158] are made about HT phenomena. Some of the fundamental experimental models through which perforated obstacles have been studied are highlighted in Table 2.

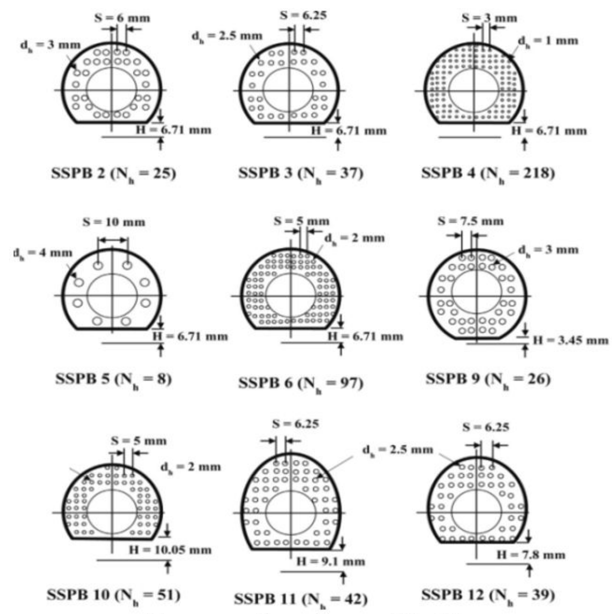
El Habet *et al.* [119] investigated the performances of new baffle designs experimentally in a rectangular HE. They have tested partial tilting with different angles whereas perforation ratios were also different. They obtained considerably high HT enhancement values compared to the smooth HE and developed new correlations for the estimation of Nu number and f factor. Skullong *et al.* [120] conducted an experimental investigation to provide an improved thermal performance of a channel using a SAH with wavy-groove and delta-wing VGs configurations integrated together on the absorber. Their results clearly indicated that the maximum enhancement in thermal performance for specific porosity and distance ratios existed for integrated devices, which provided significant improvements compared to individual configurations. In the research work, for drying, Khanlari *et al.* [121] developed parallel-pass solar collectors (SCs) with different baffling configurations, whereas for the enhancement they studied plus-type VGs in the presence of holes. Their results showed that thermal efficiencies were in the range between 62.10% and 75.11%, with the highest efficiency of about 84.30% in the case of double VGs at higher rate of mass flow, with maximum deviation of prediction against the experimental data as 9.5%.

Meanwhile, Liu *et al.* [122] have experimentally addressed the performance of perforated 90° ribs in augmenting HT inside a cooling channel; it was found that HT enhancement improved behind the ribs, the recirculation flow reduced and there is a slight disturbance in the reattachment region of flow, which is promising for turbine blade cooling applications. Further, Varol *et al.* [123] studied experimentally and numerically the convective HT and fluid dynamics of two parallel streams with different thermal profiles, using perforated passive obstructions with the purpose of controlling fluid flow and the convective mixing patterns, showing increased thermal mixing by increasing temperature differences, while positive effects of higher values of porosity upon mixing performance were also presented. On the other hand, Vaisi *et al.* [124] conducted studies on influences of twisted tape VGs, continuous and discontinuous, with and without perforations, on flow and HT in double HEs. Their results

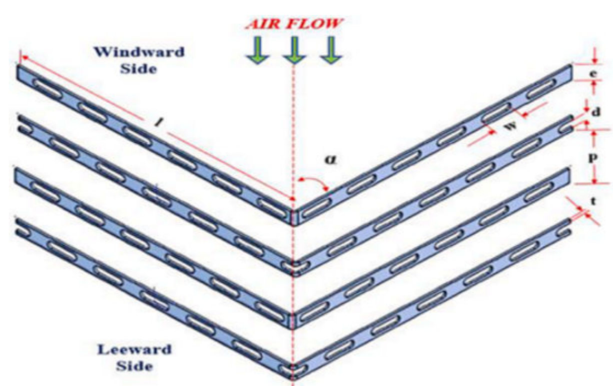
<table>
<caption>TABLE II. Experimental investigations of HEs with perforated obstacles.</caption>
<tr><th>Authors</th><th>Computational configuration</th></tr>
<tr><td>Skullong et al. [120]</td><td>

Perforated delta-wing VGs</td></tr>
<tr><td>Khanlari et al. [121]</td><td>
Perforated plus-baffles</td></tr>
<tr><td>Liu et al. [122]</td><td>

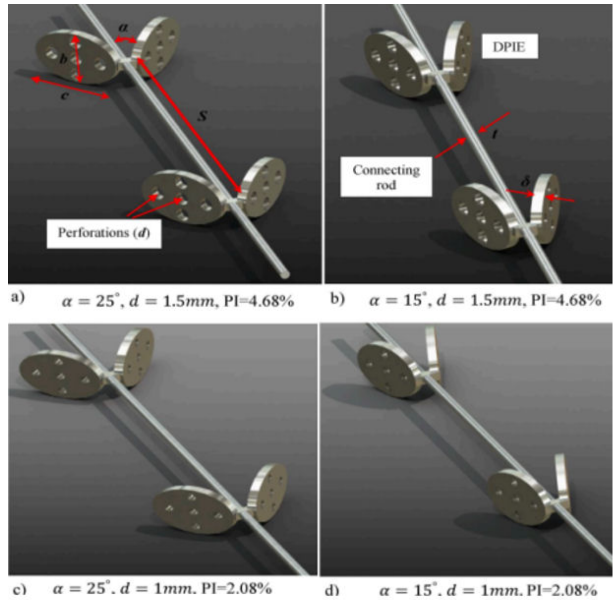
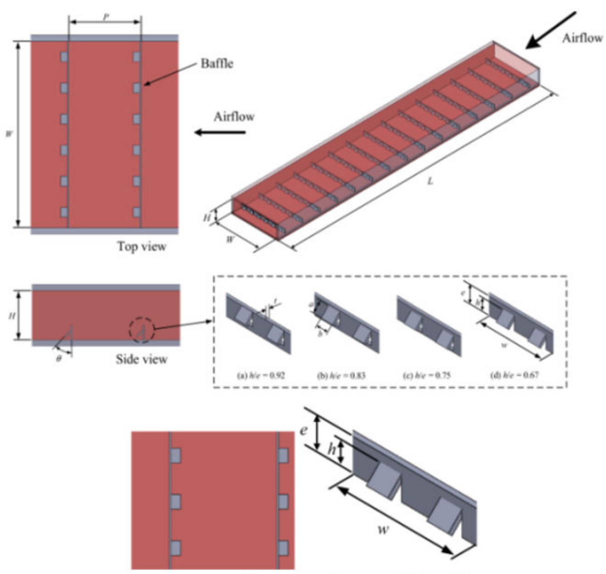
Perforated ribs</td></tr>
</table>

<table>
<tr><th>Authors</th><th>Computational configuration</th></tr>
<tr><td>Salem et al. [132]</td><td>


Segmental perforated baffles</td></tr>
<tr><td>Khoshvaght-Aliabadi et al. [133]</td><td>


Corrugated/perforated fins</td></tr>
<tr><td>Pandey and Kumar [137]</td><td>


V-baffle with staggered hole arrays</td></tr>
</table>

Authors	**Computational configuration**
Nakhchi *et al*. [148]	 *Perforated elliptic turbulators*
Eiamsa-Ard *et al*. [154]	 *Semi-circular perforated baffles*

showed that the discontinuous VG improved HT by 8.2%, with a reduction in pressure drop of 9.8% compared to its continuous counterpart.

On the other hand, Vaisi *et al*. [124] conducted studies on influences of twisted tape VGs, continuous and discontinuous, with and without perforations, on flow and HT in double HEs. Their results showed that the discontinuous VG improved HT by 8.2%, with a reduction in pressure drop of 9.8% compared to its continuous counterpart. Also, the study of Chin *et al.* [125] on the effect of staggered pin fins with perforations to enhance HT rates indicates that an increase in the number and diameter of holes on each pin gives a 45% rise in Nu number compared with solid pins. Awasarmol *et al.* [126], in their investigation, studied HT enhancement with the help of an experimental study in perforated fin arrays at different perforation ratios, inclination angles, and fin configurations under forced convection. Significant enhancements were noted when the findings were compared to solid fins. Tandel and Modi [127] presented a solar combi-system with double-pass SAHs, where significant enhancement in thermal performance was noted with perforated baffles.

Chamoli [128] conducted an experimental optimization technique to enhance the geometry of a duct system with perforated V-shaped VGs. Whereas, Chamoli and Thakur [129] experimentally analyzed that a duct system with perforated V-baffles roughened surface for SAH was better compared to a smooth duct showing enhancements of 2.57 times in Nu number and 5.96 times in frottement. In particular, the highest thermohydraulic performance was obtained for an open area ratio of 24% and roughness pitch of 2.5. Recently, Chang *et al.* [130] also proposed a HT enhancement approach for plate inserts with periodic oblique VGs together with perforated slots to improve the HT of a HE with increased resulting Nu numbers across the system and minimized flow resistance.

Ghanbari *et al.* [131] conducted an experiment on the convective HT and flow characteristics of nanoporous graphene-reinforced nanofluids. It was demonstrated that 0.2 wt% addition of nanoporous graphene increased the thermal conductivity by 12.4% and the average coefficient of HT by 39.4%. Besides that, the use of such non-Newtonian nanofluids with perforated circular VGs gave rise to an increase in the value of average thermal performance factor by 29% throughout the tested turbulence regime, hence advancing recommendations for the design of more efficient thermal systems. In another related study, Salem *et al.* [132] have conducted experimental studies on water flow within the annular zone of dual tube HEs using both no perforation and segmented perforated VG configurations. Based on their measurements, they identified that the change in design parameters in the latter resulted in a considerable difference in the characteristics of both convective HT and friction loss and provided the correlations for a concentric tube HE fitted with such VGs. Khoshvaght-Aliabadi *et al.* [133] conducted an experimental performance evaluation of perforated wavy fins in plate HEs, while the results indicated that these provided a higher HT rate as well as lower f factors when compared to conventional fins. Their study also highlighted the use of Al_2O_3/water nanofluids.

Further, Khoshvaght-Aliabadi *et al.* [134] investigated the performance of twisted-VGs mounted inside a duct under various aperture designs, different aerodynamic attachments, and their interactive effects. Their study showed that while solid models had some advantages in 0° twisted-VGs, the aerodynamic attachments enhanced performance quite drastically in 90° and 180° twisted-VGs, realizing maximum performance indices at Re number 1643. Pankaj *et al.* [135] did experimental work on natural convection HT enhancement with perforated fin arrays and, among other things, established optimal configurations such as 4 mm diameter perforations at 45° with constant pitch performing well in horizontal rectangular arrays with 10 mm spacing. In another direction, Hassan *et al.* [136] conducted an experimental performance test of flat plate SAHs using double pass (DP) configuration arrangement. They tested heaters fitted with V-corrugated-perforated absorbers. The obtained results showed that the corrugated-perforated SAH gave better daily energy and exergy efficiencies and the minimum energy cost, particularly at the 2/3 DP case.

In the experimental investigation performed by Pandey and Kumar [137], an attempt was made to enhance the performance of a SAH channel using perforated V-VGs. Based on the results, they found that among the V-down VGs studied, the best thermohydraulic performance factor and the highest thermal and effective efficiencies under turbulent airflow were for V-up VGs. The work carried out by Saravanan *et al.* [138] focused on a SAH featuring staggered multiple C-shape finned absorber plates through an experimental performance evaluation of various flow and geometric parameters for the optimization in thermal performance. The enhancements in HT with fins over the absorbers with smooth plates were observed to be very significant. Karabacak and Yakar [139] studied the effect of perforations strategically placed on finned HEs to enhance convective HT. They concluded that the perforations, which they arranged in a specific pattern on each of the circular fins, served to induce turbulence close to the tube surface; thus, a considerable enhancement of Nu numbers about 12% was reported in the range above critical Re values compared to imperforate fin. Besides that, correlations for the Re and Nu numbers, above and below the critical values, were established and those referring to pressure drops in flow areas.

Promvonge *et al.* [140] performed an experimental test of louver-punched V-VGs in a SAH duct. It was reported that this type of VGs reduced the pressure drag and improved thermal efficiency. Their optimum value of performance was 1.5, and for a louver angle was 45°. Numerical simulation results agreed well with the experimental ones. The investigations by Khargotra *et al.* [141] involved very extensive testing and evaluation of the effect of various design parameters of perforated V-VGs on airflow dynamics and thermal performance inside a rectangular channel. In these studies, they found that indeed the hybrid BWM-CODAS architecture was the best decision-making framework for determining an optimum SAH design alternative. Along the same lines, Khargotra *et al.* [142] designed and optimized a water heating setup with delta VGs having perforations, chosen as the most suitable configuration that meets the preset performance criteria; sensitivity analysis was also performed, in this respect, ensuring the effectiveness of the proposed framework.

Huang and Liu [143] studied the effect of the optimal design parameters on the thermal management in a heat sink with the introduction of a delta winglet VG to improve its effectiveness, and they proved by experimental verification that it may be improved by an increase in Re numbers. El Habet *et al.* [144] examined the hydrothermal characteristics influenced by VGs in a rectangular channel. Different baffle perforation ratios have been considered for both inline and staggered arrangements. Maximum performance extraction has been considered in the case of a staggered arrangement with solid baffles at Re = 12,000. Molki and Hashemi-Esfahanian [145] measured HT by convection behind a perforated obstruction in a rectangular conduit using a mass transfer technique to obtain local transfer rates. Further, Singh *et al.* [146], in order to investigate thermal and hydraulic performance of perforated V-VGs inserted in a double pass SAH, have presented correlation of various parameters with Nu number and frottement, showing notable enhancement in thermo-hydraulic performance by the use of perforated V-VGs compared to plain surfaces.

The other experimental study of Singh *et al.* [147], recording the same VGs texture in double pass SAH, also registered a significant improvement in overall performance over continuous rib roughness and hence spoke for the effectiveness of perforation in application to artificial roughness also. Nakhchi *et al.* [148] found that dual perforation turbulators in the inclined elliptic shape inside double-tube HEs increased the HT by 217.4% and fluid mixing to give the maximum efficiency value of 1.849 for specific perforation sizes beyond Re numbers from 5,000 to 18,000. Along the related line, an exergetic efficiency analysis performance evaluation method was developed by Fan *et al.* [149] to study a HE system using perforated twisted VGs and indicated that variation of perforation density increases the thermal-fluid performance first, up to the point where an optimal efficiency can be reached after which it decreases, while Re and magnetic field intensity have positive influence on system performance, these changes result in ideal value of perforation ratio and considerable improvement of HT efficiency was revealed using the exergy efficiency approach. This concept was also realized by Sheikholeslami and Ganji [150] during their experimental studies using perforated turbulators in a double-tube HE, optimizing geometrical parameters with the aim of enhancing HT. They determined that heat transfer increases with aperture ratio and temperature difference decreases with the pitch ratio. Buchlin [151] found that when using perforated rib structures in a turbulent boundary layer, a three-fold increase in localised heat improvement was achieved over solid ribs. Here, the optimum geometric parameters were given as a rib spacing ratio of 5 and 0.53 open area factor. Overall, it was noted that these could be applied for a range of duct Re numbers from 30,000 to 60,000.

Nuntadusit *et al.* [152] experimentally conducted studies on the interactions between thermal processes and fluid motion over a channel with transverse perforated ribs. The investigations were made on the variation in perforation angle and hole location. Sara *et al.* [153] studied the enhancements in HT and pressure fluctuations in the flow over a channel using perforated rectangular VGs, affixed onto a level surface, and reached to the conclusion that whereas the use of solid blocks led to an increased HT at the expenses of eventual losses in energy, the presence of perforations in the VGs can achieve energy gains around 40%. Studying other geometries, the influence of wing arrangement on HT and pressure drop in a duct fitted with perforated transverse baffles with square-wing geometry was analyzed by Eiamsa-Ard *et al.* [154]. Their work demonstrated that this kind of wing arrangement increased the rate of HT while reducing airflow resistance compared to solid transverse baffles.

Eiamsa-ard *et al.* [155] investigated the effects of using perforated V-baffles with delta-wing configurations (DW-PVBs) inside a duct on HT and friction loss. In their experimentations, they identified that at diminished angles of attack of the delta-wings, θ, the HT enhanced while flow resistance diminished. Concretely, DW-PVBs of $\theta = 22.5^\circ$ ensured the best performances with the highest value of performance equal to 1.91. It was also achievable for the DW-PVBs to reduce the friction factors by 13.64–17.26% compared to solid V-baffles. Bhattacharyya *et al.* [156] conducted an experimental study on perforated angular-cut baffles in turbulent flow; it was observed that among the tested geometries, alternate segmental baffles (ASB) showed the best HT augmentation with an enhanced Nu number as high as 42.18% over segmental baffles (SB), while proposing correlations between Nu, friction factor, and the examined parameters that indicated TPFs greater than unity for all cases. In search of more enhancements, Gel'Fand *et al.* [157] carried out experiments to investigate the interaction of plane shock waves with triangular pressure distributions and perforated VGs, and to measure the parameters of reflected waves, the amplitude and impulse attenuation coefficients versus barrier permeability, and quenching coefficients for an arrangement of baffles in series. Rahman [158] experimentally investigated a new axial HE that utilized perforated circular baffle plates with rectangular air deflector inserts for enhanced air-side turbulence and surface HT rates; substantial thermal enhancement at certain inclination angles and pitch ratios was depicted for the HE compared to those fitted with segmental baffle plates under identical conditions.

4. Practical applications

The effective impact of perforated obstacles on the dynamics of fluid flow makes their role imperative in most applied and industrial fields. In general, these components are very important in improving performance, efficiency, and control in most engineering systems.

Perforated baffles, employed in a wide number of industrial equipment such as HEs, chemical reactors, and distillation columns (Bruno *et al.* [159]; Nasyrlayev *et al.* [160]; Norman *et al.* [161]; and Ibrahim *et al.* [162]) improve fluid mixing, and enhance HT rates. Such baffles cause turbulence, disturb the laminar flow, and act to enhance convective HT with improved mass transfer for optimum process efficiency.

The application in HEs to aerospace engineering, Bhambere *et al.* [163]; Sakanova [164]; and Al-Damook *et al.* [165] highlighted perforated fins as one of the key elements in improving convective HT rates for thermal dissipation management. In comparison with non-perforated fins, perforated obstacles manage to dissipate heat effectively due to an increase in the exposed surface area and also due to an enhancement in the value of the convective HT coefficient, which helps to avoid overheating and promotes extending the operational lifespan of the component.

Perforated ribs also play an important role in turbomachinery, gas turbine blades, and HEs (Choi *et al*. [166]; Ye *et al*. [167]; and Chung *et al*. [168]), mainly for boundary layer control and enhancement of HT. The perforated ribs create streamwise vortices and enhance mixing in boundary layers that delays the separation and reduces pressure losses, thereby enhancing the system efficiency as a whole. In addition, the delay in fouling and sedimentation in fluid systems enhances operational reliability by stimulation of self-cleaning mechanisms and hindrance of particle deposition.

Further, perforated VGs applied in aerospace, automotive, and HVAC systems (Hasan *et al.* [169]; Heriyani *et al*. [170]; and Effendi *et al*. [171]), regulate flow structures to enhance aerodynamic performance while controlling boundary layer transitions. Their enhancement of convective HT coefficient augmentation in thermal management systems maintains temperature uniformity and carries out efficient HT.

Furthermore, perforated turbulators, integral to HEs, boilers, and air ducts (Assari *et al*. [172]; Srivastava *et al*. [173]; Bhattacharyya *et al*. [174]; and Sharma *et al*. [175]) improve the convective HT rates and enhance fluid mixing, besides fouling reduction. By inducing controlled turbulence and breaking laminar boundary layers, turbulators enhance the convective HT coefficient, hence enhancement of thermal performance and efficiency. Also, they allow for uniform temperature distribution, thereby preventing local 'hot' or 'cold' spots in HT systems and permitting stability of operation.

In other words, it points out that the general application of perforated obstructions acts to underline the very principle underlying the optimization of fluid flow, HT, and performance of an aerodynamic nature in a large number of industries and engineering applications. These flexible elements raise the efficiency and productivity of the system and allow the development of various sustainable and energy-efficient technologies.

5. Future research

The exploitation of perforated obstacles for HT enhancement in HE opens various ways for a multitude of new avenues in the field of research and innovation. Further directions could be pursued by the researchers for the advance of the field in the following ways.

The future work may conduct systematic parametric studies in the optimization of geometric parameters of perforated obstacles. Using state-of-the-art computational tools and optimization algorithms, one is able to choose an optimal shape of the perforation, its size, arrangement, and spacing for maximum HT enhancement factor with minimum loss of pressure drop and consumption of material.

The integration of multi-physics modeling and simulation techniques will provide an in-depth understanding of the complicated fluid flow and HT phenomena associated with perforated obstacles. This kind of coupling between fluid dynamics, HT, and structural mechanics simulations can clarify the interplay among flow behavior, HT enhancement, and structural integrity-and hence allow the extraction of appropriate general design guidelines.

Hybrid approaches that can marry perforated obstacles with other HT enhancement techniques may yield some synergistic benefits. Investigations that incorporate perforated obstacles with surface modifications, secondary flow inducers, and phase change materials are used to explore novel ways to further enhance HT rates and overall thermal efficiencies in HEs.

Several experimental investigations need to be performed under real operation conditions to validate the numerical simulations so that the actual application of perforated obstacles in HEs is allowed. The collaborations with industrial partners will allow the technology transfer and faster diffusion of the solutions of perforated obstacle HT enhancement in HVAC, automotive, aerospace, and renewable energy systems.

6. Conclusions

We have reviewed in this work the performance enhancement of HEs using perforated obstacles. In fact, with deeper analysis of both numerical simulation and experimental investigations, the use of perforated obstacles was found to enhance HT significantly.

We have reconsidered the spectrum of approaches to HT enhancement in HEs, from passive to active techniques, underlining the peculiar advantages coming from using perforated obstacles. In fact, this latter proved to be a promising avenue thanks to tangible improvements in flow dynamics and thermal characteristics.

A key feature of our review was the analysis of several parameters that influence the performance of perforated obstructions. Some of the operating and geometrical parameters related to hole dimensions and shapes were studied in detail to establish the boundaries of their effects on heat transfer enhancement. These data provide the basis for an optimum design for specific applications.

Further, we found critical applications in which HEs with perforated barriers prove to be very effective. The versatility of the approach from industrial processes to HVAC systems testifies to the potential to affect significant changes across many industries depending on the effectiveness of heat-exchange mechanisms.

Our review also provides useful recommendations for further research studies in this area. Further promising lines of investigation concern the exploration of new geometrical arrangements, advanced materials, and the detailed investigation of the fluid flow mechanism.

Numerical analyses presented in the work, combined with experimental validation, therefore show that perforated obstacles have the potential to cause a revolution in efficiency in HE performance. In fact, this new approach ushers in a new frontier in efficiency and sustainability regarding thermal management systems through the reduction of pressure drop and enhancement of HT coefficients.

1. R. Rebhi, Y., Menni, G., Lorenzini, and H. Ahmad, Forcedconvection heat transfer in solar collectors and heat exchangers: a review, Journal of Advanced Research in Applied *Sciences and Engineering Technology* **26** (2022) 1, https://doi.org/10.37934/araset.26.3.115
2. H. Ahmad, N. Sakhri, Y. Menni, M. Omri, and H. Ameur, Experimental study of the efficiency of earth-toair heat exchangers: Effect of the presence of external fans, *Case Studies in Thermal Engineering* **28** (2021) 101461, https://doi.org/10.1016/j.csite.2021.101461
3. F. Djeffal, L. Bordja, R. Rebhi, M. Inc, H. Ahmad, F. Tahrour, , ... and T. M. Jawa, Numerical investigation of thermal-flow characteristics in heat exchanger with various tube shapes, *Applied Sciences* **11** (2021) 9477. https://doi.org/10.3390/app11209477
4. F. Tahrour, H. Ahmad, H. Ameur, T. Saeed, H. Abu-Zinadah, and Y. Menni, 3D numerical study and comparison of thermalflow performance of various annular finned-tube designs, *Journal of Ocean Engineering and Science* **8** (2023) 294, https://doi.org/10.1016/j.joes.2022.02.009
5. N. Sakhri, Y. Menni, A. J. Chamkha, M. Salmi, and H. Ameur, Earth to air heat exchanger and its applications in arid regions-an updated review, *Tecnica Italiana Ital. J. Eng. Sci.* **64** (2020) 83-90.
6. N. Sakhri, Y. Menni, A. J. Chamkha, G. Lorenzini, H. Ameur, N. Kaid, and M. Bensafi, Experimental study of an earth-to-air heat exchanger coupled to the solar chimney for heating and cooling applications in arid regions, *Journal of Thermal Analysis and Calorimetry* **145** (2021) 3349, https://doi.org/10.1007/s10973-020-09867-6
7. N. Sakhri, A. Moussaoui, Y. Menni, M. Sadeghzadeh, and H. Ahmadi, New passive thermal comfort system using three renewable energies: Wind catcher, solar chimney and earth to air heat exchanger integrated to real-scale test room in arid region (Experimental study), *International Journal of Energy Research* **45** (2021) 2177, https://doi.org/10.1002/er.5911
8. C. H. Phillips, G. Lauschke, and H. Peerhossaini, Intensification of batch chemical processes by using integrated chemical reactor-heat exchangers, *Applied thermal engineering* **17** (1997) 809, https://doi.org/10.1016/S1359-4311(96)00061-0
9. P. L. Orts-Gonzalez, P. K. Zachos, G.D. Brighenti, The impact of heat exchanger degradation on the performance of a humid air turbine system for power generation, *Applied Thermal Engineering* **149** (2019) 1492, https://doi.org/10.1016/j.applthermaleng.2018.12.061
10. H. Zheng, G. Tian, S. Zeng, Z. Zhang, Z. Lv, and Q. Wang, Study on the performance of multi-medium heat exchanger in solar composite refrigeration system, *Applied Thermal Engineering* (2024) 122826. https://doi.org/10.1016/j.applthermaleng.2024.122826
11. S. Liu, and M. Sakr, A comprehensive review on passive heat transfer enhancements in pipe exchangers, *Renewable and sustainable energy reviews* **19** (2013) 64, https://doi.org/10.1016/j.rser.2012.11.021
12. M. Sheikholeslami, M. Gorji-Bandpy, and D. D. Ganji, Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices, *Renewable and Sustainable Energy Reviews* **49** (2015) 444-469.
13. R. Andrzejczyk, T. Muszynski, and P. Kozak, Experimental and computational fluid dynamics studies on straight and U-bend double tube heat exchangers with active and passive enhancement methods, *Heat Transfer Engineering* **42** (2021) 167, https://doi.org/10.1080/01457632.2019.1699279
14. S. Thapa, S. Samir, K. Kumar, and S. Singh, A review study on the active methods of heat transfer enhancement in heat exchangers using electroactive and magnetic materials, *Materials Today: Proceedings* **45** (2021) 4942, https://doi.org/10.1016/j.matpr.2021.01.382
15. A. A. Abd, M. Q. Kareem, and S. Z. Naji, Performance analysis of shell and tube heat exchanger: Parametric study, *Case studies in thermal engineering* **12** (2018) 563, https://doi.org/10.1016/j.csite.2018.07.009
16. M. M. Rashidi, I. Mahariq, M. Alhuyi Nazari, O. Accouche, and M. M. Bhatti, Comprehensive review on exergy analysis of shell and tube heat exchangers. *Journal of Thermal Analysis and Calorimetry* **147** (2022) 12301, https://doi.org/10.1007/s10973-022-11478-2
17. O. P. Arsenyeva, L. L. Tovazhnyanskyy, P. O. Kapustenko, and G. L. Khavin, Mathematical modelling and optimal design of plate-and-frame heat exchangers, *Chemical Engineering Transactions* **18** (2009) 791, https://repository.kpi.kharkov.ua/handle/KhPI-Press/27669
18. O.P. Arsenyeva, L. L. Tovazhnyansky, P. Kapustenko, and G.L. Khavin, Optimal design of plate-and-frame heat exchangers for efficient heat recovery in process industries, *Energy* **36** (2011) 4588, https://doi.org/10.1016/j.energy.2011.03.022
19. P. Geiser, and V. Kottke, Transport phenomena in fluid flow of finned tube heat exchangers. In: Y. Tanida, H. Miyashiro, (eds) Flow Visualization VI. 1992. Springer, Berlin, Heidelberg.
20. A. A. Bhuiyan, and A. S. Islam, Thermal and hydraulic performance of finned-tube heat exchangers under different flow ranges: A review on modeling and experiment, International *Journal of Heat and Mass Transfer* **101** (2016) 38, https://doi.org/10.1016/j.ijheatmasstransfer.2016.05.022
21. S. Basavarajappa, G. Manavendra, and S. B. Prakash, A review on performance study of finned tube heat exchanger. *In Journal of Physics: Conference Series* **1473** (2020) 012030, https://doi.org/10.1088/1742-6596/1473/1/012030
22. K. M. Stone, Review of literature on heat transfer enhancement in compact heat exchangers, Air Conditioning and Refrigeration Center TR-105 (1996)
23. R. K. Shah, Advances in science and technology of compact heat exchangers, *Heat Transfer Engineering* **27** (2006) 3, https://doi.org/10.1080/01457630600559462

24. Q. Li, G. Flamant, X. Yuan, P. Neveu, and L. Luo, Compact heat exchangers: A review and future applications for a new generation of high temperature solar receivers, *Renewable and Sustainable Energy Reviews* **15** (2011) 4855, https://doi.org/10.1016/j.rser.2011.07.066

25. M. Konopacki, M. Kordas, K. Fijałkowski, and R. Rakoczy, Computational fluid dynamics and experimental studies of a new mixing element in a static mixer as a heat exchanger, *Chemical and Process Engineering* **36** (2015) 59, https://doi.org/10.1515/cpe-2015-0005

26. Y. Qi, Y. Kawaguchi, R. N. Christensen, and J. L. Zakin, Enhancing heat transfer ability of drag reducing surfactant solutions with static mixers and honeycombs, *International Journal of Heat and Mass Transfer* **46** (2003) 5161, https://doi.org/10.1016/S0017-9310(03)00221-7

27. A. Maxson, L. Watson, P. Karandikar, and J. Zakin, Heat transfer enhancement in turbulent drag reducing surfactant solutions by agitated heat exchangers, *International Journal of Heat and Mass Transfer* **109** (2017) 1044, https://doi.org/10.1016/j.ijheatmasstransfer.2017.01.098

28. M. Molki, and P. Damronglerd, Electrohydrodynamic enhancement of heat transfer for developing air flow in square ducts, *Heat Transfer Engineering* **27** (2006) 35, https://doi.org/10.1080/01457630500341748

29. S. Laohalertdecha, P. Naphon, and S. Wongwises, A review of electrohydrodynamic enhancement of heat transfer, *Renewable and Sustainable Energy Reviews* **11** (2007) 858, https://doi.org/10.1016/j.rser.2005.07.002

30. Y. B. Wang *et al*., Heat transfer enhancement by electrohydrodynamics in wavy channels, *Applied Thermal Engineering* **236** (2024) 121556, https://doi.org/10.1016/j.applthermaleng.2023.121556

31. S. W. Chen *et al*., Experimental test and empirical correlation development for heat transfer enhancement under ultrasonic vibration, *Applied Thermal Engineering* **143** (2018) 639, https://doi.org/10.1016/j.applthermaleng.2018.07.133

32. M. Setareh, M. Saffar-Avval, and A. Abdullah, Experimental and numerical study on heat transfer enhancement using ultrasonic vibration in a double-pipe heat exchanger, *Applied Thermal Engineering* **159** (2019) 113867, https://doi.org/10.1016/j.applthermaleng.2019.113867

33. D. Zhang, E. Jiang, J. Zhou, C. Shen, Z. He, and C. Xiao, Investigation on enhanced mechanism of heat transfer assisted by ultrasonic vibration, *International Communications in Heat and Mass Transfer* **115** (2020) 104523, https://doi.org/10.1016/j.icheatmasstransfer.2020.104523

34. K. Shoele, and R. Mittal, Computational study of flowinduced vibration of a reed in a channel and effect on convective heat transfer, *Physics of Fluids* **26** (2014) 127103, https://doi.org/10.1063/1.4903793

35. D. Duan, P. Ge, W. Bi, and J. Ji, Numerical investigation on the heat transfer enhancement mechanism of planar elastic tube bundle by flow-induced vibration, *International Journal of Thermal Sciences* **112** (2017) 450, https://doi.org/10.1016/j.ijthermalsci.2016.11.003

36. J. Fu, X. Miao, Q. Zuo, H. Tang, Y. Li, Y. Zhang, and B. Sunden, Heat transfer and field synergy characteristics in a rectangular unit channel under mechanical vibration, *International Communications in Heat and Mass Transfer* **136** (2022) 106176, https://doi.org/10.1016/j.icheatmasstransfer.2022.106176

37. Y. Menni, A. J. Chamkha, C. Zidani, and B. Benyoucef, Heat and nanofluid transfer in baffled channels of different outlet models, *Mathematical Modelling of Engineering Problems* **6** (2019) 21, https://doi.org/10.18280/mmep.060103

38. Y. Menni, A. J. Chamkha, M. Ghazvini, M. H. Ahmadi, H. Ameur, A. Issakhov, and M. Inc, Enhancement of the turbulent convective heat transfer in channels through the baffling technique and oil/multiwalled carbon nanotube nanofluids, *Numerical Heat Transfer, Part A: Applications* **79** (2020) 311, https://doi.org/10.1080/10407782.2020.1842846

39. Y. Menni, A. J. Chamkha, and H. Ameur, Advances of nanofluids in heat exchangers-A review, *Heat Transfer* **49** (2020) 4321, https://doi.org/10.1002/htj.21829

40. R. Maouedj, Y. Menni, M. Inc, Y. M. Chu, H. Ameur, and G. Lorenzini, Simulating the Turbulent Hydrothermal Behavior of Oil/MWCNT Nano fluid in a Solar Channel Heat Exchanger Equipped with Vortex Generators, *Computer Modeling in Engineering and Sciences* **126** (2021) 855, https://doi.org/10.32604/cmes.2021.014524

41. A. Mahammedi, H. Ameur, Y. Menni, and D. M. Medjahed, Numerical study of turbulent flows and convective heat transfer of Al2O3-water nanofluids in a circular tube, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* **77** (2021) 1, https://doi.org/10.37934/arfmts.77.2.112

42. A. Boursas, M. Salmi, G. Lorenzini, H. Ahmad, Y. Menni, and D. Fridja, Enhanced heat transfer by oil/multi-walled carbon nano-tubes nanofluid, *Annales de Chimie Science des Materiaux* **45** (2021) 93, https://doi.org/10.18280/acsm.450201

43. G. Wang, Z. Zhang, R. Wang, and Z. Zhu, A review on heat transfer of nanofluids by applied electric field or magnetic field, *Nanomaterials* **10** (2020) 2386, https://doi.org/10.3390/nano10122386

44. M. Bezaatpour, and M. Goharkhah, Convective heat transfer enhancement in a double pipe mini heat exchanger by magnetic field induced swirling flow, *Applied Thermal Engineering* **167** (2020) 114801, https://doi.org/10.1016/j.applthermaleng.2019.114801

45. X. Zhang, and Y. Zhang, Experimental study on enhanced heat transfer and flow performance of magnetic nanofluids under alternating magnetic field, *International Journal of Thermal Sciences* **164** (2021) 106897, https://doi.org/10.1016/j.ijthermalsci.2021.106897

46. A. J. Chamkha, Y. Menni, and H. Ameur, Thermalaerodynamic performance measurement of air heat transfer fluid mechanics over s-shaped fins in shell-and-tube heat exchangers, *Journal of Applied and Computational Mechanics* **7** (2021) 1931, https://doi.org/10.22055/JACM.2020.32107.1970

47. F. Djeffal, F. Tahrour, L. Bordja, A. Akgul, . Jarrar, J. Asad, and Y. Menni, Three-dimensional assessment of thermalhydraulic behaviour in heat exchangers fitted by wavy annular fins, *Thermal Science*, **26** (2022) 485, https://doi.org/10.2298/TSCI22S1485D

48. R. Rebhi, H. Ahmad, Y. Zhao, Y. Menni, and G. Lorenzini, Numerical assessment of an air-heat exchanger channel with staggered attached rectangular baffles and in-line detached square fins, *Thermal Science*, **27** (2023) 343, https://doi.org/10.2298/TSCI23S1343R

49. S. Hammid *et al*., Overall assessment of heat transfer for a rarefied flow in a microchannel with obstacles using lattice Boltzmann method, *Comput. Model. Eng. Sci,* **138** (2024) 273-299.

50. S. Eiamsa-ard, P. Promvonge, Numerical study on heat transfer of turbulent channel flow over periodic grooves, *International Communications in Heat and Mass Transfer* **35** (2008) 844, https://doi.org/10.1016/j.icheatmasstransfer.2008.03.008

51. P. M. Ligrani, G. I. Mahmood, J. L. Harrison, C. M. Clayton, and D. L. Nelson, Flow structure and local Nusselt number variations in a channel with dimples and protrusions on opposite walls, *International Journal of Heat and Mass Transfer* **44** (2001) 4413, https://doi.org/10.1016/S0017-9310(01)00101-6

52. Y. Menni, H. Ahmad, H. Ameur, S. Askar, T. Botmart, M. Bayram, and G. Lorenzini, Effects of two-equation turbulence models on the convective instability in finned channel heat exchangers, *Case Studies in Thermal Engineering* **31** (2022) 101824, https://doi.org/10.1016/j.csite.2022.101824

53. R. Chatys, and L. J. Orman, Technology and properties of layered composites as coatings for heat transfer enhancement, *Mechanics of Composite Materials* **53** (2017) 351, https://doi.org/10.1007/s11029-017-9666-8

54. D. H. Nguyen, and H. S. Ahn, A comprehensive review on micro/nanoscale surface modification techniques for heat transfer enhancement in heat exchanger, International *Journal of Heat and Mass Transfer* **178** (2021) 121601, https://doi.org/10.1016/j.ijheatmasstransfer.2021.121601

55. M. C. Korti *et al*., Optimizing solar water heater performance through a numerical study of zig-zag shaped tubes, *Thermal Science* **27** (2023) 3143, https://doi.org/10.2298/TSCI2304143K

56. A. Youcef, M. C. Korti, Y. Menni, and H. Ameur, Investigation of the thermal behavior of water flow within parallel tubes in a solar collector, *Journal of applied research and technology* **20** (2022) 679, https://doi.org/10.22201/icat.24486736e.2022.20.6.1110

57. Y. Menni, A. J. Chamkha, A. Azzi, A., and C. Zidani, Numerical analysis of fluid flow and heat transfer characteristics of a new kind of vortex generators by comparison with those of traditional vortex generators, *International Journal of Fluid Mechanics Research* **47** (2020) 23, https://doi.org/10.1615/InterJFluidMechRes.2019026753

58. Y. Menni, A. J. Chamkha, A. Azzi, and C. Zidani, Numerical analysis of fluid flow and heat transfer characteristics of a new kind of vortex generators by comparison with those of traditional vortex generators, International *Journal of Fluid Mechanics Research* **47** (2020) 23, https://doi.org/10.1615/InterJFluidMechRes.2019026753

59. M. Salmi *et al*., Turbulent flows around rectangular and triangular turbulators in baffled channels: a computational analysis, *Thermal Science* **26** (2022) 191, https://doi.org/10.2298/TSCI22S1191S

60. Y. Menni, and A. Azzi, Numerical analysis of thermal and aerodynamic fields in a channel with cascaded baffles, *Periodica Polytechnica Mechanical Engineering* **62** (2018) 16, https://doi.org/10.3311/PPme.10613

61. Y. Menni, and A. Azzi, Design and performance evaluation of air solar channels with diverse baffle structures, *Computational Thermal Sciences* **10** (2018) 225, https://doi.org/10.1615/ComputThermalScien.2018025026

62. Y. Menni, A. J. Chamkha, G. Lorenzini, and B. Benyoucef, Computational fluid dynamics based numerical simulation of thermal and thermo-hydraulic performance of a solar air heater channel having various ribs on absorber plates, *Mathematical Modelling of Engineering Problems* **6** (2019) 170, https://doi.org/10.18280/mmep.060203

63. Y. Menni, A; J. Chamkha, C. Zidani, and B. Benyoucef, Heat transfer in air flow past a bottom channel wallattached diamond-shaped baffle-using a CFD technique, *Periodica Polytechnica Mechanical Engineering* **63** (2019) 100, https://doi.org/10.3311/PPme.12490

64. Y. Menni, A; J. Chamkha, A. Azzi, C. Zidani, and B. Benyoucef, Study of air flow around flat and arcshaped baffles in shell-and-tube heat exchangers, *Mathematical Modelling of Engineering Problems* **6** (2019) 77, https://doi.org/10.18280/mmep.060110

65. H. Ameur, D. Sahel, and Y. Menni, Numerical investigation of the performance of perforated baffles in a plate-fin heat exchanger, *Thermal Science* **25** (2021) 3629, https://doi.org/10.2298/TSCI190316090A

66. H. Ameur, D. Sahel, and Y. Menni, Enhancement of the cooling of shear-thinning fluids in channel heat exchangers by using the V-baffling technique, *Thermal Science and Engineering Progress* **18** (2020) 100534, https://doi.org/10.1016/j.tsep.2020.100534

67. A. J. Chamkha, and Y. Menni, Hydrogen Flow over a Detached V-Shaped Rib in a Rectangular Channel, *Mathematical Modelling of Engineering Problems* **7** (2020) 178, https://doi.org/10.18280/mmep.070202

68. M. Salmi *et al*.,, Improved heat transfer in w-baffled air-heat exchangers with upper-inlet and lower-exit, *Mathematical Modelling of Engineering Problems* **8** (2021) 1, https://doi.org/10.18280/mmep.080101

69. D. M. Medjahed *et al*., Details on the hydrothermal characteristics within a solar-channel heat-exchanger provided with staggered t-shaped baffles, *Energies* **14** (2021) 6698. https://doi.org/10.3390/en14206698

70. B. Afif, M. Salmi, A. Akgul, R. Jarrar, J. Asad, and Y. Menni, Comparative analysis of solar air channels, z-shaped obstacles added to improve flow structure, Haut du formulaire. *Thermal Science* **26** (2022) 201, https://doi.org/10.2298/TSCI22S1201A

71. V. Solano-Olivares, S. Cuevas, A. Figueroa, and D. R. DomÃ-nguez-Lozoya, Interaction of inertia and magnetic force in the liquid metal flow past a magnetic obstacle. *Physics of Fluids*, **36** (2024) 084105.
72. V. Solano-Olivares, S. Cuevas, and A. Figueroa, Magnetic fin for heat transfer enhancement in liquid metal duct flow. *Magnetohydrodynamics* (0024-998X), **58** (2022) 379.
73. M. Gallo, H. Nemati, B. J. Boersma, R. Pecnik, P. Attrotto, and P. Colonna, "Magnetic-ribs" in fully developed laminar liquid-metal channel flow. *International Journal of Heat and Fluid Flow*, **56** (2015) 198-208.
74. X. Zhang and H. Huang, Heat transfer enhancement of MHD flow by a row of magnetic obstacles, *Heat Transfer Research*, **46** (2015) 1101,
75. S. Eiamsa-Ard, S. Sripattanapipat, A. Saysroy, P. Promvonge, N. Maruyama, and M. Hirota, Heat transfer distribution and flow characteristics in a channel with perforated-baffles, *Energy Reports* **8** (2022) 420, https://doi.org/10.1016/j.egyr.2022.10.079
76. H. L. Liu, H. Y. Guo, Z. L. Xie, and L. Sang, Numerical investigations for optimizing a novel micro-channel sink with perforated baffles and perforated walls, *International Communications in Heat and Mass Transfer* **126** (2021) 105342, https://doi.org/10.1016/j.icheatmasstransfer.2021.105342
77. J. Liu, S. Hussain, W. Wang, L. Wang, G. Xie, and B. SundÃ©n, Heat transfer enhancement and turbulent flow in a rectangular channel using perforated ribs with inclined holes, *Journal of Heat Transfer* **141** (2019) 041702, https://doi.org/10.1115/1.4042841.
78. A. D. Tuncer, A. Amini, and A. Khanlari, Developing an infrared-assisted solar drying system using a vertical solar air heater with perforated baffles and nanoenhanced black paint, *Solar Energy* **263** (2023) 111958, https://doi.org/10.1016/j.solener.2023.111958.
79. D. Sahel, H. Ameur, R. Benzeguir, and Y. Kamla, Enhancement of heat transfer in a rectangular channel with perforated baffles, *Applied Thermal Engineering* **101** (2016) 156,
80. S. Chamoli, ANN and RSM approach for modeling and optimization of designing parameters for a V down perforated baffle roughened rectangular channel, *Alexandria Engineering Journal* **54** (2015) 429, https://doi.org/10.1016/j.aej.2015.03.018.
81. S. Chamoli, and N. S. Thakur, Exergetic performance evaluation of solar air heater having V-down perforated baffles on the absorber plate, *Journal of Thermal Analysis and Calorimetry* **117** (2014) 909, https://doi.org/10.1007/s10973-014-3765-8.
82. K. S. Kandukuri, P. K. Sharma, and R. K. Arun, A comparative assessment of distributive mode active solar dryers: Flat plate collector vs evacuated tube collector with thermal energy storage and perforated baffled trays, *Solar Energy* **271** (2024) 112421,
83. Y. Wang, C. S. Oon, J. J. Foo, M. V. Tran, S. R. Nair, and F. W. Low, Numerical investigation of thermo-hydraulic performance utilizing clove-treated graphene nanoplatelets nanofluid in an annular passage with perforated curve fins. *Results in Engineering* **17** (2023) 100848.
84. G. Wang, T. Hai, J. K. S. Paw, J. Pasupuleti, and A. N. Abdalla, Numerical and ensemble machine learning-based investigation of the energy and exergy yields of a concentrating photovoltaic thermal device equipped with a perforated twisted tube turbulator, *Engineering Analysis with Boundary Elements*, **155** (2023) 754.
85. Y. Wang, J. J. Foo, M. V. Tran, S. R. Nair, and C. S. Oon, Numerical investigation of thermo-hydraulic performance of perforated rectangular and sinusoidal vortex generators in a doublepipe heat exchanger, *Journal of Thermal Analysis and Calorimetry* (2024) 1-18.
86. K. Song, Y. He, Q. Zhang, X.Wu, A. He, and Q. Hou, Thermal performance promotion of a novel double-tube heat exchanger by helical fin with perforations, *International Communications in Heat and Mass Transfer* **150** (2024) 107189.
87. Haut du formulaire K. Boukhadia, H. Ameur, D. Sahel, and M. Bozit, Effect of the perforation design on the fluid flow and heat transfer characteristics of a plate fin heat exchanger, *International Journal of Thermal Sciences* **126** (2018) 172-180.
88. M. F. Ismail, M. O. Reza, M. A. Zobaer, and M. Ali, Numerical investigation of turbulent heat convection from solid and longitudinally perforated rectangular fins, *Procedia Engineering* **56** (2013) 497-502.
89. J. Li, X. Ling, and H. Peng, Field synergy analysis on convective heat transfer and fluid flow of a novel triangular perforated fin, *International journal of heat and mass transfer* **64** (2013) 526-535.
90. A. H. Ganie, A. A. Memon, M. A. Memon, A. M. Al-Bugami, K. Bhatti, and I. Khan, Numerical analysis of laminar flow and heat transfer through a rectangular channel containing perforated plate at different angles, *Energy Reports* **8** (2022) 539.
91. H. Ameur, and Y. Menni, Laminar cooling of shear thinning fluids in horizontal and baffled tubes: Effect of perforation in baffles, *Thermal Science and Engineering Progress* **14** (2019) 100430.
92. Y. Zhao, M. Lu, Y. Li, Y. Wang, and M. Ge, Numerical investigation of an exhaust thermoelectric generator with a perforated plate, *Energy* **263** (2023) 125776.
93. N. Biçer, T. Engin, H. Yaşar, E. Büyükkaya, A. Aydın, and A. Topuz, Design optimization of a shell-and-tube heat exchanger with novel three-zonal baffle by using CFD and taguchi method, *International Journal of Thermal Sciences* **155** (2020) 106417.
94. R. B. Pérez, A. M. Pérez, and D. S. Suárez, Influence of the punched holes on thermohydraulic performance and flow pattern of rectangular channels with a pair of perforated vortex generators, *International Journal of Heat and Mass Transfer* **184** (2022) 122291.
95. M. Tavakoli, and M. R. Soufivand, Investigation of entropy generation, PEC, and efficiency of parabolic solar collector containing water/Al2O3-MWCNT hybrid nanofluid in the presence of finned and perforated twisted tape turbulators using a two-phase flow scheme, *Engineering Analysis with Boundary Elements* **148** (2023) 324-335.

96. M. E. Nakhchi, M. Hatami, and M. Rahmati, Effects of CuO nano powder on performance improvement and entropy production of double-pipe heat exchanger with innovative perforated turbulators, *Advanced Powder Technology* **32** (2021) 3063.

97. S. Javanmard, and A. Ashrafizadeh, A comparative numerical study on heat transfer and pressure drop characteristics of perforated ribs, *International Journal of Thermal Sciences* **191** (2023) 108373.

98. A. Hedau, and R. P. Saini, Thermo-hydraulic performance of double pass solar air heater duct having semi-circular tubes and perforated blocks as artificial roughness, *Renewable Energy* **205** (2023) 543-562.

99. Z. Zou, Z. Zhu, Q. Zhang, and P. Yang, Numerical investigation on the performance of a new type of perforated-serrated fins for plate-fin heat exchangers in cryogenic helium systems, *Cryogenics*, **136** (2023) 103761.

100. H. Sun, H. Ma, L. Yan, H. Fu, Y. Luan, and P. Zunino, Numerical simulations on the performance of transpiration cooling implemented with perforated flat plates, *Applied Thermal Engineering* **238** (2024) 121943.

101. A. H. Dastbelaraki, M. Yaghoubi, M. M. Tavakol, and A. Rahmatmand, Numerical analysis of convection heat transfer from an array of perforated fins using the Reynolds averaged Navier-Stokes equations and large-eddy simulation method, *Applied Mathematical Modelling* **63** (2018) 660-687.

102. S. E. Razavi, T. Adibi, and S. Faramarzi, Impact of inclined and perforated baffles on the laminar thermo-flow behavior in rectangular channels, *SN Applied Sciences* **2** (2020) 1-9.

103. S. Ghanbari, and K. Javaherdeh, Investigation of applying nanoporous graphene non-Newtonian nanofluid on rheological properties and thermal performance in a turbulent annular flow with perforated baffles, *Journal of Thermal Analysis and Calorimetry* **139** (2020) 629-647.

104. M. A. Xue, P. Z. Lin, J. H. Zheng, Y. X. Ma, X. L. Yuan, and V. T. Nguyen, Effects of perforated baffle on reducing sloshing in rectangular tank: experimental and numerical study, *China Ocean Engineering* **27** (2013) 615-628.

105. B. Qi, and R. Yuan, Heat transfer enhancement in a twodimensional channel with perforated rectangular blocks using multi-layered porous foam, *Journal of Thermal Analysis and Calorimetry* **141** (2020) 1817-1827.

106. N. Y. Godi, Constructal Solid and Perforated Fin Installation in a Combined Microchannel Heat Sink for Maximum Heat Transfer, *Journal of The Institution of Engineers* (India): Series C (2024) 1-14.

107. N. Y. Godi, and M. O. Petinrin, Heat Transfer Analysis in Constructal Designed Microchannels with Perforated Micro Fins, *Journal of The Institution of Engineers* (India): Series C (2023) 1-12.

108. A. Gautam, L. Pandey, and S. Singh, Influence of perforated triple wing vortex generator on a turbulent flow through a circular tube, *Heat and Mass transfer* **54** (2018) 2009-2021.

109. N. Van Hap, P. T. Nhan, H. P. Hien, and N. M. Phu, Thermohydraulic performance augmentation in a solar air heater using a perforated circular segment vortex generator, *Environmental Science and Pollution Research* **30** (2023) 65338-65350.

110. B. Lertnuwat, The effect of the hole position on trapezoidal winglet vortex generators in a rectangular-duct-type solar air heater, *Journal of Mechanical Science and Technology* **36** (2022) 6345-6354.

111. Z. Esmaeili, and S. Rashidi, Entropy production analysis for nanofluid flow through a channel with perforated transverse twisted-baffles, Energy Sources, *Part A: Recovery, Utilization, and Environmental Effects* 1-20 (2022)

112. S. K. Jain, R. Misra, A. Kumar, and G. D. Agrawal, Thermal performance investigation of a solar air heater having discrete Vshaped perforated baffles, *International Journal of Ambient Energy* **43** (2022) 243-251.

113. M. R. Shaeri, and T. C. Jen, Turbulent heat transfer analysis of a three-dimensional array of perforated fins due to changes in perforation sizes, *Numerical Heat Transfer, Part A: Applications* **61** (2012) 807-822.

114. M. R. Shaeri, and M. Yaghoubi, Thermal enhancement from heat sinks by using perforated fins, *Energy conversion and Management* **50** (2009) 1264.

115. M. R. Shaeri, and M. Yaghoubi, Numerical analysis of turbulent convection heat transfer from an array of perforated fins, *International journal of heat and fluid flow* **30** (2009) 218.

116. X. Huang, L. Wang, and X. Li, Research on thermal performance and pressure loss of a new perforated-folded baffle solar air collector, *Numerical Heat Transfer, Part A: Applications* (2023) 1-20.

117. F. N. Barzoki, G. A. Sheikhzadeh, M. K. Aliabadi, and A. A. A. Arani, Assessment of vortex generator shapes for enhancing thermohydraulic performance of fluid flow in a channel equipped with perforated chevron plate-fin, *International Journal of Numerical Methods for Heat and Fluid Flow* **31** (2021) 1790.

118. B. Rostane, and S. Abboudi, Numerical Study of Laminar Fluid Flow Around Two HeatedWall-Mounted Perforated Cubes in Tandem Arrangement, *International Journal of Heat and Technology* **40** (2022) 157.

119. M. A. El Habet, S. A. Ahmed, and M. A. Saleh, The effect of using staggered and partially tilted perforated baffles on heat transfer and flow characteristics in a rectangular channel, *International Journal of Thermal Sciences* **174** (2022) 107422.

120. S. Skullong, P. Promvonge, C. Thianpong, and M. Pimsarn, Thermal performance in solar air heater channel with combined wavy-groove and perforated-delta wing vortex generators, *Applied Thermal Engineering* **100** (2016) 611-620.

121. A. Khanlari *et al.*, Experimental and numerical study of the effect of integrating plus-shaped perforated baffles to solar air collector in drying application, *Renewable Energy* **145** (2020) 1677-1692.

122. J. Liu, S. Hussain, W. Wang, G. Xie, and B. SundÃ©n, Experimental and numerical investigations of heat transfer and fluid flow in a rectangular channel with perforated ribs, *International Communications in Heat and Mass Transfer* **121** (2021) 105083.

123. Y. Varol, B. Kok, H. Ayhan, and H. F. Oztop, Experimental study and Large Eddy Simulation of thermal mixing phenomena of a parallel jet with perforated obstacles, *International Journal of Thermal Sciences* **111** (2017) 1-17.

124. A. Vaisi, R. Moosavi, M. Lashkari, and M. M. Soltani, Experimental investigation of perforated twisted tapes turbulator on thermal performance in double pipe heat exchangers, *Chemical Engineering and Processing-Process Intensification* **154** (2020) 108028.

125. S. B. Chin, J. J. Foo, Y. L. Lai, and T. K. K. Yong, Forced convective heat transfer enhancement with perforated pin fins. *Heat and Mass Transfer* **49** (2013) 1447-1458.

126. U. V. Awasarmol, A. T. Pise, J. D. Patil, L. D. Jathar, and R. R. Verma, Experimental investigation of heat transfer enhancement by using perforated fin array having different perforation ratios, angle of inclination and configuration of fins under forced convection condition, *International Communications in Heat and Mass Transfer* **147** (2023) 106995.

127. H. U. Tandel, and K. V. Modi, Experimental assessment of double-pass solar air heater by incorporating perforated baffles and solar water heating system, *Renewable Energy* **183** (2022) 385-405.

128. S. Chamoli, A Taguchi approach for optimization of flow and geometrical parameters in a rectangular channel roughened with V down perforated baffles, *Case Studies in Thermal Engineering* **5** (2015) 59-69.

129. S. Chamoli, and N. S. Thakur, Thermal behavior in rectangular channel duct fitted with v-shaped perforated baffles, *Heat Transfer Engineering* **36** (2015) 471-479.

130. S. W. Chang, T. W. Chen, and Y. W. Chen, Detailed heat transfer and friction factor measurements for square channel enhanced by plate insert with inclined baffles and perforated slots, *Applied Thermal Engineering* **159** (2019) 113856.

131. S. Ghanbari, and K. Javaherdeh, Thermal performance enhancement in perforated baffled annuli by nanoporous graphene non-Newtonian nanofluid, *Applied Thermal Engineering* **167** (2020) 114719.

132. M. R. Salem, M. K. Althafeeri, K. M. Elshazly, M. G. Higazy, and M. F. Abdrabbo, Experimental investigation on the thermal performance of a double pipe heat exchanger with segmental perforated baffles, *International Journal of Thermal Sciences* **122** (2017) 39-52. Haut du formulaire

133. M. Khoshvaght-Aliabadi, M. Tatari, and M. Salami, Analysis on Al2O3/water nanofluid flow in a channel by inserting corrugated/ perforated fins for solar heating heat exchangers, *Renewable Energy* **115** (2018) 1099-1108.

134. M. Khoshvaght-Aliabadi, M. Farsi, S. M. Hassani, Abu-N.H. Hamdeh, and A. Alimoradi, Surface modification of transversely twisted-turbulator using perforations and winglets: An extended study, *International Communications in Heat and Mass Transfer* **120** (2021) 105020.

135. S. Pankaj, B. Santosh, K. Kishor, and J. Sarang, Experimental investigation of heat transfer by natural convection with perforated pin fin array, *Procedia Manufacturing* **20** (2018) 311-317.

136. H. Hassan, M. S. Yousef, and S. Abo-Elfadl, Energy, exergy, economic and environmental assessment of double pass Vcorrugated- perforated finned solar air heater at different air mass ratios, *Sustainable Energy Technologies and Assessments* **43** (2021) 100936.

137. R. Pandey, and M. Kumar, Efficiencies assessment of an indoor designed solar air heater characterized by V baffle blocks having staggered racetrack-shaped perforation geometry, *Sustainable Energy Technologies and Assessments*, **47** (2021) 101362.

138. A. Saravanan, M. Murugan, M. S. Reddy, P. Ranjit, P. V. Elumalai, P. Kumar, and S. R. Thermo-hydraulic performance of a solar air heater with staggered C-shape finned absorber plate, *International Journal of Thermal Sciences* **168** (2021) 107068.

139. R. Karabacak, and G. Yakar, Forced convection heat transfer and pressure drop for a horizontal cylinder with vertically attached imperforate and perforated circular fins, *Energy conversion and management* **52** (2011) 2785-2793.

140. P. Promvonge, P. Promthaisong, and S. Skullong, Heat transfer augmentation in solar heat exchanger duct with louver-punched V-baffles, *Solar Energy* **248** (2022) 103-120.

141. R. Khargotra, T. Alam, K. Thu, K. AndrÃ¡s, and T. Singh, Optimization of design parameter of V-shaped perforated blocks in rectangular duct of solar air heater by using hybrid BWMCO-DAS technique, *Solar Energy Materials and Solar Cells* **264** (2024) 112627.

142. R. Khargotra, R. Kumar, A. Sharma, and T. Singh, Design and performance optimization of solar water heating system with perforated obstacle using hybrid multi-criteria decision-making approach, *Journal of Energy Storage* **63** (2023) 107099.

143. C. H. Huang, and L. W. Liu, Optimal position and perforated radius of punched vortex generators for heat sink, *Case Studies in Thermal Engineering* **32** (2022) 101916.

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

145. M. Molki, and A. Hashemi-Esfahanian, Turbulent convective mass transfer downstream of a perforated baffle blockage, *International journal of heat and fluid flow* **13** (1992) 116-123.

146. V. P. Singh *et al.*, Heat transfer and friction factor correlations development for double pass solar air heater artificially roughened with perforated multi-V ribs, *Case Studies in Thermal Engineering* **39** (2022) 102461.

147. V. P. Singh, S. Jain, and J. M. L. Gupta, Performance assessment of double-pass parallel flow solar air heater with perforated multi-V ribs roughness-Part B, *Experimental Heat Transfer* **35** (2022) 1059-1076.

148. M. E. Nakhchi, M. Hatami, and M. Rahmati, Experimental investigation of performance improvement of double-pipe heat exchangers with novel perforated elliptic turbulators, *International Journal of Thermal Sciences* **168** (2021) 107057.

149. F. Fan, C. Qi, Q. Liu, and M. Sheikholeslami, Effect of twisted turbulator perforated ratio on thermal and hydraulic performance of magnetic nanofluids in a novel thermal exchanger system, *Case Studies in Thermal Engineering* **22** (2020) 100761.

150. M. Sheikholeslami, and D. D. Ganji, Heat transfer improvement in a double pipe heat exchanger by means of perforated turbulators, *Energy Conversion and management* **127** (2016) 112.

151. J. M. Buchlin, Convective heat transfer in a channel with perforated ribs, *International journal of thermal sciences* **4** (2002) 332-340.

152. C. Nuntadusit, M. Wae-Hayee, A. Bunyajitradulya, and S. Eiamsa-ard, Thermal visualization on surface with transverse perforated ribs, *International communications in heat and mass transfer* **39** (2012) 634-639.

153. O. N. Sara, T. Pekdemir, S. I. N. A. N. Yapici, and M. Yilmaz, Heat-transfer enhancement in a channel flow with perforated rectangular blocks, *International Journal of Heat and Fluid Flow* **22** (2001) 509-518.

154. S. Eiamsa-Ard, A. Phila, M. Pimsarn, N. Maruyama, and M. Hirota, Heat transfer mechanism and thermal performance of a channel with square-wing perforated transverse baffles installed: effect of square-wing location, *Journal of Thermal Analysis and Calorimetry* **148** (2023) 3835.

155. S. Eiamsa-ard, A. Phila, C. Thianpong, V. Chuwattanakul, N. Maruyama, and M. Hirota, Enhanced heat transfer performance in channel with delta-wing perforated V-type baffles, *Journal of Thermal Analysis and Calorimetry* **148** (2023) 11283.

156. S. Bhattacharyya, D. K. Vishwakarma, V. Goel, S. Chamoli, A. Issakhov, and J. P. Meyer, Thermodynamics and heat transfer study of a circular tube embedded with novel perforated angularcut alternate segmental baffles, *Journal of Thermal Analysis and Calorimetry* **145** (2021) 1445,

157. B. E. Gel'Fand, S. P. Medvedev, A; N. Polenov, and S. A. Tsyganov, Interaction of unsteady pressure waves and perforated baffles, *Fluid Dynamics*, **22** (1987) 969-972.

158. M. A. Rahman, Effectiveness of a tubular heat exchanger and a novel perforated rectangular flow-deflector type baffle plate with opposing orientation, *World Journal of Engineering* (2023)

159. P. Bruno, G. Di Bella, and M. De Marchis, Perforated baffles for the optimization of disinfection treatment, *Water*, **12** (2020) 3462.

160. N. Nasyrlayev, M. A. Kizilaslan, A. T. Kurumus, E. Demirel, and M. M. Aral, A perforated baffle design to improve mixing in contact tanks, *Water*, **12** (2020) 1022.

161. M. A. Norman, and M. N. Hassan, Flow Visualization of Perforated Baffles and Impellers for Stirred Tank Reactor with Single Stage Rushton Turbine, *Journal of Complex Flow*, **1** (2019)

162. B. S. Ibrahim, M. H. Abdel-Aziz, E. Z. El-Ashtoukhy, T. M. Zewail, A. A. Zatout, and G.H. Sedahmed, Cementation of copper on zinc in agitated vessels equipped with perforated baffles as turbulence promoters, Mining, *Metallurgy and Exploration* **38** (2021) 1203.

163. M. B. Bhambere, S. S. Chaudhari, and G. K. Awari, Review on design and heat transfer analysis of solid and perforated fins for the enhancement of thermal performance of heat sinks. In 2019 International Conference on Innovative Trends and Advances in Engineering and Technology (ICITAET) (2019) (pp. 210-214). IEEE.

164. A. Sakanova, Heat transfer enhancement of perforated pin heat sink in future aircraft applications, *Applied Thermal Engineering* **124** (2017) 315.

165. A. Al-Damook, N. Kapur, J. L. Summers, and H. M. Thompson, Computational design and optimisation of pin fin heat sinks with rectangular perforations, *Applied Thermal Engineering* **105** (2016) 691-703.

166. J. H. Choi, S. Mhetras, J. C. Han, S. C. Lau, and R. Rudolph, Film cooling and heat transfer on two cutback trailing edge models with internal perforated blockages, *J. Heat Transfer* **130** (2018) 012201,

167. Y. Ye, X. Li, J. Ren, and H. Jiang, Effect of holes shape on cooling performance of trailing edge of gas turbine blade with perforated blockages with inclined holes. In Turbo Expo: Power for Land, Sea, and Air, *American Society of Mechanical Engineers*, **50879**, (2017) V05AT16A004.

168. H. Chung, J. S. Park, H. S. Sohn, D. H. Rhee, and H. H. Cho, Trailing edge cooling of a gas turbine blade with perforated blockages with inclined holes. In Turbo Expo: Power for Land, Sea, and Air American *Society of Mechanical Engineers.* **55140** (2013) V03AT12A043 .

169. M. J. Hasan, K. Tawkir, and A. A. Bhuiyan, Improvement of an exhaust gas recirculation cooler using discrete ribbed and perforated louvered strip vortex generator, *International Journal of Thermofluids* **13** (2022) 100132.

170. O. Heriyani, M. Djaeni, A. K. Putri, Perforated concave rectangular winglet pair vortex generators enhance the heat transfer of air flowing through heated tubes inside a channel, *Results in Engineering* **16** (2022) 100705.

171. Y. Effendi, A. Prayogo, M. Syaiful, M. Djaeni, and E. Yohana, Effect of perforated concave delta winglet vortex generators on heat transfer and flow resistance through the heated tubes in the channel, *Experimental Heat Transfer*, **35** (2022) 553.

172. M. Assari, S. Banihashemi, M. Setareh, and A. M. Nargesi Motlagh, Numerical study of thermal characteristics and pressure drop in a pipe equipped with innovative perforated and hollow spherical inserts, *Journal of Thermal Analysis and Calorimetry*, **148** (2023) 11325.

173. G. P. Srivastava, A. K. Patil, and M. Kumar, Parametric effect of diverging perforated cones on the thermo-hydraulic performance of a heat exchanger tube. *Heat and Mass Transfer*, **57** (2021) 1425.

174. S. Bhattacharyya, M. Pathak, M. Sharifpur, S. Chamoli, S., and D. R. Ewim, Heat transfer and exergy analysis of solar air heater tube with helical corrugation and perforated circular disc inserts, *Journal of Thermal Analysis and Calorimetry* **145** (2021) 1019.

175. S. L. Sharma, S. Singh, A. Debbarma, and K. S. Mehra, Experimental assessment of thermal performance and fluid flow characteristics of perforated hollow elliptical insert in a tube heat exchanger, *Arabian Journal for Science and Engineering* **48** (2023) 11499.