International Communications in Heat and Mass Transfer 164 (2025) 108937

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Performance enhancement of flat plate heat exchangers through baffle integration: Thermal, flow, and entropy analysis

M. Nithya [a,*], M. Senthil Vel [b], C. Sivaraj [a]

[a] *Department of Mathematics, PSG College of Arts and Science, Coimbatore 641014, Tamil Nadu, India.*
[b] *Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore 641062, Tamil Nadu, India.*

ARTICLE INFO

Keywords:
Plate heat exchanger
Entropy
Flow maldistribution
Baffles
Thermal performance
Predictive models

ABSTRACT

The Plate Heat Exchangers (PHEs) are of essential integral component in industries in diverse aspects and can handle even the minimal temperature differential. This study builds on previous research in a 500 × 2 MW Thermal Power Plant by introducing novel baffle designs in PHEs for the first time. These baffles were specifically developed to address the intricate geometry and complex flow dynamics of PHEs. Building on our previous work, an in-depth analysis was conducted to assess entropy generation, shear stress distribution, and the impact of these baffles on flow maldistribution and thermal performance, as quantified by the JF factor. The study employs the Realizable k-ε turbulence model with scalable wall functions, using the PISO algorithm for pressure-velocity coupling, with a second-order approximation for momentum transport equations and a first-order for turbulence equations. Results indicate a remarkable boost of 11.5 times thermal performance enhancement compared to conventional model. The wedge type experienced a turbulent kinetic energy (TKE) increase of up to 15 %, while the aerofoil exhibited a decrease of 18 %. Additionally, Witte-Shamsundar efficiency was evaluated and advanced regression models were used to predict the Nusselt number and skin friction coefficient, with Gaussian Process Regression (GPR) emerging as the most reliable model. The findings highlight the aerofoil baffles exhibited stable and consistent performance across multiple parameters unlike wedge baffles, enhancing heat exchanger performance along with effective energy utilization.

1. Introduction

Plate heat exchangers (PHEs) stand as pivotal components in numerous industrial and domestic applications, facilitating efficient heat transfer between fluid streams while occupying minimal space [1]. Their widespread adoption arises from their compact design, high thermal efficiency, and versatility across various operating conditions [2]. PHEs consist of a series of thin plates stacked together, creating alternating channels through which hot and cold fluids flow [3]. This arrangement maximizes the surface area available for heat transfer, promoting rapid and effective thermal exchange [4]. PHEs find extensive use in HVAC systems, refrigeration, power generation, chemical processing, and food industries, among others [5–7].

Recent research has primarily focused on enhancing heat transfer rates, minimizing pressure drops, mitigating fouling effects, and addressing flow maldistribution to optimize the overall performance of PHEs [8–14]. Studies have explored entropy generation in heat exchangers, aiming to understand irreversibilities in thermal processes. Sekulic [15] examined the principles of energy conversion using the second law of thermodynamics, while Bejan [16] proposed optimization strategies to reduce entropy generation by manipulating geometric parameters of flow. Further advancements by Bejan and Poulikakos [17] highlighted the role of extended surfaces in forced convection scenarios. The impact of rib spacing on entropy generation is less significant than rib height. Additionally, as rib spacing increases, its effect on entropy generation gradually diminishes [18]. These works provide fundamental insights into entropy generation and its impact on PHE efficiency; however, they do not explicitly address the role of structural modifications such as baffles in mitigating thermal losses and optimizing energy efficiency.

Fouling remains a major challenge in heat exchanger performance, leading to efficiency losses and increased maintenance costs. Studies [19–24] have emphasized the need for effective fouling mitigation strategies, particularly through velocity optimization and surface roughness management. Notably, Coletti and Macchietto [25–29] developed mathematical models for analyzing crude oil refinery heat exchangers affected by fouling, which were later extended by Bejarano

---

* Corresponding author.
E-mail address: msdnithya@gmail.com (M. Nithya).

https://doi.org/10.1016/j.icheatmasstransfer.2025.108937

especially at higher Reynolds numbers where turbulence becomes more pronounced.

The prediction results in Fig. 14. further demonstrate the robustness of GPR, showing strong alignment between true and predicted values for both Nusselt number and skin friction coefficients across configurations. This minimal deviation in GPR predictions highlights its effectiveness in accurately modeling complex heat transfer and flow dynamics influenced by aerofoil and wedge baffle structures. By employing tailored kernels and optimal hyperparameters, GPR is able to handle the nonlinear interactions efficiently, providing a reliable framework for predicting performance parameters in plate heat exchangers with modified geometries.

5. Conclusions

The simultaneous interpretation of entropy and enthalpy provides a comprehensive understanding of the enhanced performance and efficiency achieved by baffled plate heat exchangers, offering valuable insights for further research and optimization efforts in heat exchanger design and operation. Also, several other performance efficiency parameters based on the first and second law of thermodynamics are explored and compared among all the modified and conventional cases. The highlighted results are:

- The modified PHEs exhibit up to 58 % higher shear stress compared to the conventional design, with 5 wedge baffles performing best.
- The wedge configuration with five baffles experienced a maximum TKE increase of up to 15 %, while the aerofoil type exhibited a maximum TKE decrease of 18 %.
- Although the TKE of the aerofoil decreases, its thermal performance remains positively correlated. This indicates that improved thermal performance does not necessarily depend on higher turbulence levels but rather on optimizing flow dynamics to achieve effective heat transfer.
- At higher Reynolds numbers, both wedge and aerofoil baffles achieve uniform fluid distribution with minimal differences. While at lower *Re*, aerofoil baffles more effectively reduce maldistribution.
- The JF value indicates that integrating both wedge and aerofoil baffles ensures more stable and consistent performance.
- Baffled configurations improve thermal performance by up to 11.5 times over the conventional model, demonstrating a significant enhancement.
- Aerofoil baffles tends to be more stable in both WS efficiency and JF value across varying Reynolds numbers, ensuring consistent system performance.
- The Matern 5/2 kernel effectively modeled Nusselt number, while the Rational Quadratic kernel was optimal for skin friction predictions.
- Support Vector Machine (SVM) and Linear Regression showed poor performance, making them unsuitable for this dataset.
- GPR is confirmed as the most reliable model for predicting heat transfer characteristics in PHEs with aerofoil and wedge shaped baffles.

This finding provides valuable insights to enhance heat transfer performance through the different configuration of baffles within plate heat exchanger systems. The proposed modification has the potential to enhance both thermal performance and the maximum permissible operating pressure and temperature, owing to the introduction of baffles in between the plates. Furthermore, this modification is adaptable to various types of Plate Heat Exchangers (PHE), including brazed PHEs, and can be implemented across different flow configurations. Overall, these findings highlight the effectiveness of the baffled PHE design and its potential benefits for various industrial heat transfer applications. This emphasizes, further study is required to explore over the strategic placements of baffles to find the most optimum model.

CRediT authorship contribution statement

M. Nithya: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **M. Senthil Vel:** Writing – review & editing, Visualization, Software, Investigation. **C. Sivaraj:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We sincerely thank Mr. M. Muruganantham, Additional Chief Manager, and Mr. S. Ganapathi, Chief Manager at NTPL, Tuticorin, for their invaluable support, including technical assistance, data provision, and sharing their extensive expertise in the field. We extend our gratitude to PSG College of Arts and Science for their generous stipend that supported our research. Furthermore, we deeply appreciate PSG Institute of Technology and Applied Research, Coimbatore, for their project support by providing a dedicated workstation.

Data availability

Data will be made available on request.

References

[1] B. Sundén, R.M. Manglik, Plate Heat Exchangers: Design, Applications and Performance vol. 11, Wit Press, 2007.
[2] S. Kakaç, H. Liu, A. Pramuanjaroenkij, Heat Exchangers: Selection, Rating, and Thermal Design, CRC Press, 2002.
[3] W. Focke, et al., The effect of the corrugation inclination angle on the thermohydraulic performance of plate heat exchangers, Chem. Eng. Sci. 28 (1985) 1469–1479.
[4] A.C. Dimian, C.S. Bildea, A.A. Kiss, Integrated Design and Simulation of Chemical Processes, Elsevier, 2014.
[5] C.-C. Lee, İ.A. Taştemir, Direct heat exchangers in the food industry, in: Thermal Processing of Food Products by Steam and Hot Water, Elsevier, 2023, pp. 181–208.
[6] S. Tassou, et al., A review of emerging technologies for food refrigeration applications, Int. J. Refrig. 30 (2010) 263–276.
[7] Z.H. Ayub, Plate heat exchanger literature survey and new heat transfer and pressure drop correlations for refrigerant evaporators, Heat Transfer Eng. 24 (2003) 3–16.
[8] O.V. Demirskiy, et al., Prediction of fouling tendency in PHE by data of on-site monitoring. Case study at sugar factory, Therm. Sci. Eng. Prog. 128 (2018) 1074–1081.
[9] A. Sharma, S. Macchietto, Fouling and cleaning of plate heat exchangers: dairy application, Food Bioprod. Process. 126 (2021) 32–41.
[10] O. Arsenyeva, et al., The water fouling development in plate heat exchangers with plates of different corrugations geometry, Energy Rep. 32 (2022) 101310.
[11] H. Shokouhmand, M. Hasanpour, Effect of number of plates on the thermal performance of a plate heat exchanger with considering flow maldistribution, J. Energy Storage 32 (2020) 101907.
[12] B.P. Rao, S.K. Das, An experimental study on the influence of flow maldistribution on the pressure drop across a plate heat exchanger, J. Fluids Eng. 126 (2004) 680–691.
[13] P. Kapustenko, et al., PHE (plate heat exchanger) for condensing duties: recent advances and future prospects, Heat Transfer Eng. 16 (2023) 524.
[14] Z. Ma, P. Zhang, Pressure drop and heat transfer characteristics of clathrate hydrate slurry in a plate heat exchanger, Int. J. Refrig. 34 (2011) 796–806.
[15] D. Sekulic, The second law quality of energy transformation in a heat exchanger, Energy 15 (1990).
[16] A. Bejan, A study of entropy generation in fundamental convective heat transfer, Int. J. Heat Mass Transf. 22 (1979) 719–728.
[17] D. Poulikakos, A. Bejan, Fin geometry for minimum entropy generation in forced convection, Int. J. Heat Mass Transf. 25 (1982) 715–722.
[18] A. Bejan, P.A. Pfister Jr., Evaluation of heat transfer augmentation techniques based on their impact on entropy generation, Heat Mass Transf. Lett. 7 (1980) 97–106.
[19] J. Vrouwenvelder, et al., Pressure drop increase by biofilm accumulation in spiral wound RO and NF membrane systems: role of substrate concentration, flow velocity, substrate load and flow direction, Biofouling 25 (2009) 543–555.
[20] E. Ishiyama, W. Paterson, D. Wilson, Thermo-hydraulic channelling in parallel heat exchangers subject to fouling, Chem. Eng. Sci. 63 (2008) 3400–3410.

[21] B. Yeap, et al., Mitigation of crude oil refinery heat exchanger fouling through retrofits based on thermo-hydraulic fouling models, Chem. Eng. Res. Des. 82 (2004) 53–71.
[22] F.C.S. Macchietto, G.T. Polley, Effects of fouling on performance of retrofitted heat exchanger networks; a thermo-hydraulic based analysis, in: ESCAPE-20, European Symposium of Computer Aided Process Engineering, Elsevier, 2010.
[23] G. Polley, et al., Applying thermo-hydraulic simulation and heat exchanger analysis to the retrofit of heat recovery systems, Appl. Therm. Eng. 51 (2013) 137–143.
[24] P.O. Kapustenko, et al., Accounting for local thermal and hydraulic parameters of water fouling development in plate heat exchanger, Energy 174 (2019) 1049–1059.
[25] F. Coletti, S. Macchietto, A dynamic, distributed model of shell-and-tube heat exchangers undergoing crude oil fouling, Ind. Eng. Chem. Res. 50 (2011) 4515–4533.
[26] F. Coletti, S. Macchietto, N. Elvassore, Mathematical modeling of three-dimensional cell cultures in perfusion bioreactors, Ind. Eng. Chem. Res. 45 (2006) 8158–8169.
[27] S. Macchietto, et al., Fouling in crude oil preheat trains: a systematic solution to an old problem, Heat Transf. Eng. 32 (2011) 197–215.
[28] F. Coletti, S. Macchietto, G.T. Polley, Effects of fouling on performance of retrofitted heat exchanger networks: a thermo-hydraulic based analysis, Comput. Chem. Eng. 35 (2011) 907–917.
[29] F. Coletti, S. Macchietto, Refinery pre-heat train network simulation undergoing fouling: assessment of energy efficiency and carbon emissions, Heat Transf. Eng. 32 (2011) 228–236.
[30] E. Diaz-Bejarano, et al., Organic and inorganic fouling in heat exchangers–industrial case study: analysis of fouling state, Appl. Energy 206 (2017) 1250–1266.
[31] E. Diaz-Bejarano, F. Coletti, S. Macchietto, Thermo-hydraulic analysis of refinery heat exchangers undergoing fouling, AICHE J. 63 (2017) 984–1001.
[32] E. Diaz-Bejarano, F. Coletti, S. Macchietto, Modeling and prediction of shell-side fouling in shell-and-tube heat exchangers, Heat Transf. Eng. 40 (2019) 845–861.
[33] E. Diaz-Bejarano, F. Coletti, S. Macchietto, A new dynamic model of crude oil fouling deposits and its application to the simulation of fouling-cleaning cycles, AIChE J. 62 (2016) 90–107.
[34] E. Diaz-Bejarano, F. Coletti, S. Macchietto, A model-based method for visualization, monitoring, and diagnosis of fouling in heat exchangers, Ind. Eng. Chem. Res. 59 (2020) 4602–4619.
[35] E. Diaz-Bejarano, et al., Organic and inorganic fouling in heat exchangers: industrial case study analysis of fouling rate, Ind. Eng. Chem. Res. 58 (2018) 228–246.
[36] F. Coletti, et al., Impact of deposit aging and surface roughness on thermal fouling: distributed model, AIChE J. 56 (2010) 3257–3273.
[37] B. Prabhakara Rao, B. Sundén, S.K. Das, An experimental and theoretical investigation of the effect of flow maldistribution on the thermal performance of plate heat exchangers, J. Heat Transfer 127 (2005) 332–343.
[38] N. Srihari, et al., Transient response of plate heat exchangers considering effect of flow maldistribution, Int. J. Heat Mass Transf. 48 (2005) 3231–3243.
[39] H. Shokouhmand, M. Hasanpour, Effect of number of plates on the thermal performance of a plate heat exchanger with considering flow maldistribution, J. Energy Storage 32 (2020) 101907.
[40] M.M.A. Bhutta, et al., CFD applications in various heat exchangers design: a review, Appl. Therm. Eng. 32 (2012) 1–12.
[41] P. Promvonge, S. Skullong, Heat transfer in a tube with combined V-winglet and twin counter-twisted tape, Case Studies in Thermal Engineering 26 (2021) 101033.
[42] P. Promvonge, S. Tamna, M. Pimsarn, S. Kwankaomeng, Thermal performance and exergy analysis in a round tube with louvered trapezoidal winglets, International Journal of Heat and Mass Transfer 212 (2023) 124261.
[43] J. Wang, Y. Zhang, X. Huang, Y. Li, Heat transfer performance of internal flow by inserting punched and non-punched vortex generators, Int. J. Therm. Sci. 186 (2023) 108135.
[44] X. Wu, L. Yang, L. Sun, H. Tang, A comparative study of fluid flow and heat transfer in the tube with multi-V-winglets vortex generators, Appl. Therm. Eng. 236 (2024) 121448.
[45] M.A. Rahman, Thermal performance of tubular heat exchangers with the discontinuous swirl-inducing conical baffle with opposite-oriented flow deflectors, Archives of Thermodynamics 45 (1) (2024) 195–204.
[46] Y.-G. Lei, et al., Design and optimization of heat exchangers with helical baffles, Chem. Eng. Sci. 63 (2008) 4386–4395.
[47] U. Salahuddin, M. Bilal, H. Ejaz, A review of the advancements made in helical baffles used in shell and tube heat exchangers, Int. Commun. Heat Mass Transf. 67 (2015) 104–108.
[48] A.S. Ambekar, et al., CFD simulation study of shell and tube heat exchangers with different baffle segment configurations, Appl. Therm. Eng. 108 (2016) 999–1007.
[49] H. Li, V. Kottke, Effect of baffle spacing on pressure drop and local heat transfer in shell-and-tube heat exchangers for staggered tube arrangement, Int. J. Heat Mass Transf. 41 (1998) 1303–1311.
[50] M. Nithya, et al., Optimizing thermal efficiency: advancements in flat plate heat exchanger performance through baffle integration, Appl. Therm. Eng. 158 (2024) 107885.
[51] L. Witte, N. Shamsundar, A thermodynamic efficiency concept for heat exchange devices, Heat Transf. Eng. 4 (1983) 123–129.
[52] A.P. Watkinson, Deposition from crude oils in heat exchangers, Heat Transf. Eng. 28 (2007) 177–184.
[53] C.A. Bennett, et al., Observation of an isokinetic temperature and compensation effect for high-temperature crude oil fouling, Heat Transf. Eng. 30 (2009) 794–804.
[54] H. Joshi, N. Shilpi, A. Agarwal, Relate crude oil fouling research to field fouling observations, in: Proc. of Int. Conf. on Heat Exchanger Fouling and Cleaning VIII, 2009. Peer-reviewed.
[55] A. Bejan, Second law analysis in heat transfer, Energy 5 (1980) 720–732.
[56] M. Hashemian, et al., Enhancement of heat transfer rate with structural modification of double pipe heat exchanger by changing cylindrical form of tubes into conical form, Appl. Therm. Eng. 118 (2017) 408–417.
[57] M. Hashemian, S. Jafarmadar, H.S. Dizaji, A comprehensive numerical study on multi-criteria design analyses in a novel form (conical) of double pipe heat exchanger, Appl. Therm. Eng. 102 (2016) 1228–1237.
[58] B.P. Rao, S.K. Das, An experimental study on the influence of flow maldistribution on the pressure drop across a plate heat exchanger, J. Fluids Eng. 126 (2004) 680–691.
[59] J. Ham, et al., Numerical study on the flow maldistribution characteristics of a plate heat exchanger, Appl. Therm. Eng. 224 (2023) 120136.
[60] F.A. Tereda, et al., Experimental investigation on port-to-channel flow maldistribution in plate heat exchangers, Heat Transf. Eng. 28 (2007) 435–443.
[61] P.R. Bobbili, B. Sundén, S.K. Das, An experimental investigation of the port flow maldistribution in small and large plate package heat exchangers, Appl. Therm. Eng. 26 (2006) 1919–1926.
[62] M.S. Islam, S.C. Saha, Heat transfer augmentation in retrofitted corrugated plate heat exchanger, Int. J. Heat Mass Transf. 161 (2020) 120226.