Scientific Journal of Impact Factor (SJIF): 4.72
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 4, Issue 11, November -2017

Review of Experimental Analysis and Comparision of Results with Correlations developed for Colburn Factor (j) and Friction Factor (f) in Plate Fin Heat Exchangers

V. R. Chavda[1]

[1]*Lecturer in Mechanical Department, R.C.T.I., Ahmedabad*

Abstract — *In the cryogenics field, high effectiveness heat exchangers of the order of 0.96 or higher are widely used for preserving the refrigeration effect produced. So, there will be no liquid yield if the effectiveness falls below that of the design value Due to high effectiveness, low weight & compactness, the compact heat exchangers have their extensive applications in cryogenics. The plate fin heat exchangers (PFHE) is a type of compact heat exchanger which is manufactured by brazing a stack of alternate plates (parting sheets) & corrugated fins together. The exchange of heat occurs by the streams through the fins. Generally, aluminum is used for manufacturing PFHE due to their high thermal conductivity & low cost. In the plate fin heat exchanger, the pressure drop is also measured along with the effectiveness. The increase in pressure gradient can be outweighed by decreasing the passage length, so that an acceptable pressure drop can be achieved. There are enormous research is going on to make out the heat transfer phenomena & also to determine the dimensionless heat transfer coefficients that is the Colburn factor (j) and the friction factor (f). In this review paper, experimental analysis and results compared with correlations developed for colburn factor (j) and friction factor (f) for PFHE.*

Keywords-*compact heat exchangers, plate fin heat exchangers (PFHE), fins, colburn factor (j), friction factor (f), Number of Transfer Units (NTU), Reynolds Number (Re).*

I. INTRODUCTION

Heat exchangers used in cryogenic applications need to have very high effectiveness to preserve the refrigerating effect produced. Normally the heat exchangers used in liquefiers have the effectiveness of the order of 0.95 or higher. If the effectiveness of heat exchangers falls below the design value, there may not be any liquid yield [1]. The minimum effectiveness of heat exchanger devices required in regenerative refrigerators stands at 95-98%. These requirements have led to the development of a unique class of heat exchangers known as compact heat exchangers. Compact heat exchangers present a large surface area (area to volume ratio greater than 700 m^2/m^3). This requirement is only possible with Plate Fin Heat Exchangers (PFHE) only. Plate fin exchanger is a type of compact heat exchanger where the heat transfer surface area is enhanced by providing extended metal surface, interfaced between the two fluids and is called the fins. Out of the various compact heat exchangers, plate fin heat exchangers are unique due to their superior construction and performance. They are characterized by high effectiveness, compactness, low weight and moderate cost. As the name suggests, a plate fin heat exchanger (PFHE) is a type of compact exchanger that consists of a stack of alternate flat plates called parting sheets and corrugated fins brazed together as a block. Streams exchange heat by flowing along the passages made by the fins between the parting sheets. Figure 1.1 shows an exploded view of two layers of a plate fin heat exchanger. Such layers are arranged together in a monolithic block to form a heat exchanger.

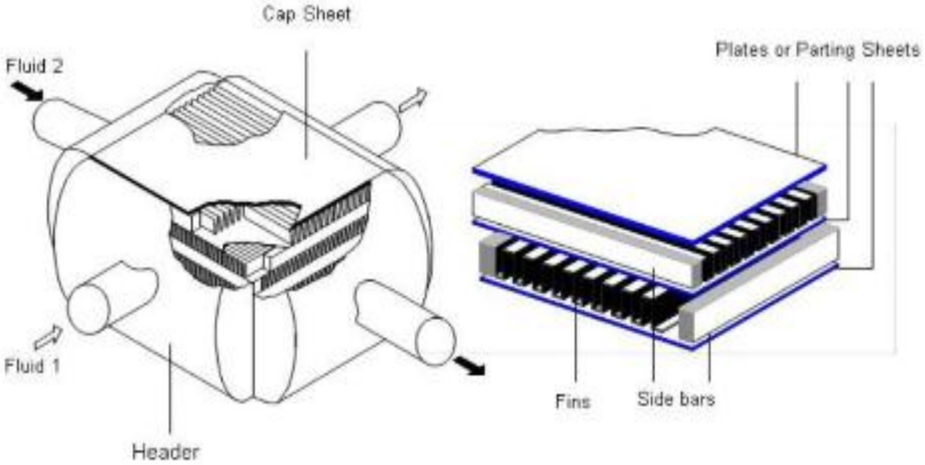

Figure 1.1: Plate fin heat exchanger assembly and details

The compact plate fin heat exchangers can be divided into various types depending on their fin structures. Some fin types are: 1. Triangular or rectangular cross-section plate fins(straight and uncut fins) 2. Wavy fins. 3. Various types of interrupted fins like offset strip fin, perforated fin, louver and pin fin. The strip fins are also known as serrated or segmented fin lance offset fin and offset fin. See figure 1.2 for details.

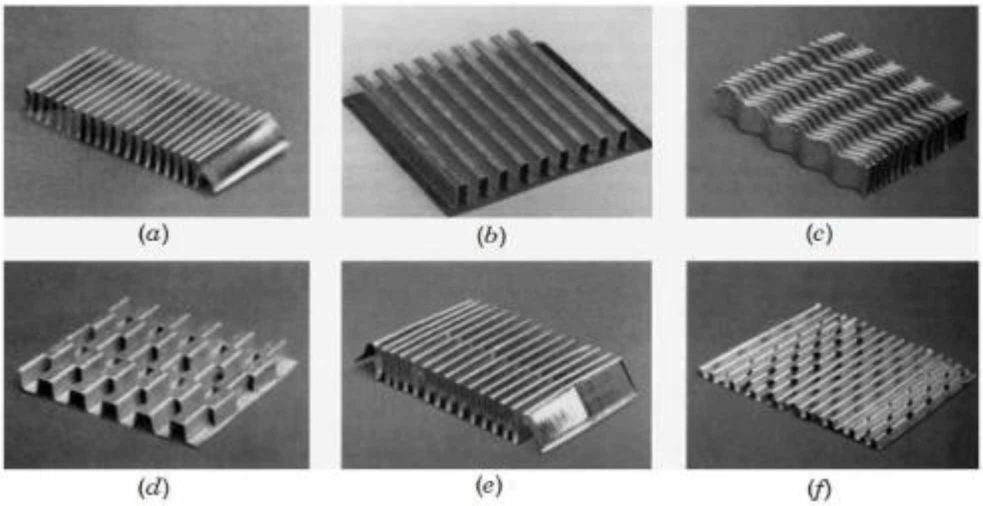

Figure 1.2 Plate fin heat exchangers having corrugated fin geometries (a) Triangular plain fin (b) Rectangular plain fin (c) Wavy fin (d) Serrated or offset strip fin (e) Multi-louver fin (f) Perforated fin

II. DEVELOPMENT OF EXPERIMENTAL ANALYSIS AND RESULTS IN PLATE FIN HEAT EXCHANGERS (PFHE)

Fehle et al. [1] found the heat transfer behaviour of the compact plate fin heat exchanger by applying holographic interferometry. For this, he enabled a non-invasive and inertia less visualization of the temperature field. Then from the constant temperature line at the wall of the temperature field, he determined the local Nusselt number. For determining the effect of corner radii of the heat metal sheets, they first investigated the transfer of heat in plane fin arrangements. They also examined the increase of turbulence by the effect of circular segments in the inclined, non-staggered and staggered arrangements. After the determining the average Nusselt number they got the conclusion that the rate of heat transfer is highest in the in the non-staggered geometry and the staggered geometry achieved the best volume goodness factor. Ranganayakulau et al. [2] analyzed the cross flow plate fin, cross flow tube fin, parallel plate fin and the counter-flow plate fin heat exchangers by taking the effect of heat conduction in the longitudinal direction across the heat exchanger wall by using finite element method. They observed that the performance declination of cross flow type heat exchangers is higher compared to the counter-flow and parallel flow heat exchangers for all the cases. This occurrence of the distribution of temperature is two dimensional. Sanaye and Hajabdollahi [3] applied ε-NTU method, they calculated the effectiveness and the pressure drop of the heat exchanger. The fin pinch, height of the pin, offset length of the fin, flow length of the cold stream, no-flow length and flow length of the hot stream are considered as the six design parameters. They used non-dominated sorting genetic algorithm (NSGA-II) for getting the maximum effectiveness and minimum total yearly cost as two objective functions.

Rao and Patel [4] thermodynamically optimized the cross flow PFHE by using particle swarm optimization (PSO). The reduction of entropy generation for a given space restriction for specific heat duty, reduction of total volume and reduction of total unwanted cost are the basic objective functions, which are treated individually. Hajabdollahi at el. [5] presented a thermal model and optimally designed a compact heat exchanger. Fin pitch, the height of the fin, flow length of the cold stream, no-flow length and flow length of the hot stream are the five deign parameters. By using CFD analysis along with ANN (Artificial Neural Network), they developed a relation between the Colburn factor (j) and Fanning friction factor (f). Zhang et al. [6] examined evaporative mist pre-cooling, deluge cooling and combined cooling schemes for enhancing the performance of the heat exchanger. Pingaud et al. [7] performed both the steady state simulation and the dynamic simulation of the plate fin exchanger. By using the modeling based on mass balance, momentum balance and energy balance, they developed an algorithm for multi-fluid and multi passage PFHEs for both the transient and steady-state simulations. For treating the counter current flow and for solving the model equations involving the partial differentiation, they adopted an integration scheme which is implicit in nature. Menzel and Hecht [8] found that the heat exchanger performance decreases by the slog flow reversal, two-phase up-flow in PFHEs and they liquid logging involved in the heat exchanger surfaces. So, they adopted a special care by selecting wide boiling range fluid mixtures which evaporates at high NTU values at relatively low gas fluxes. Flow condition of non-refluxes needs a large gas mass flux, thus a higher pressure drop. Dubrovsky [9] investigated a new convective heat transfer augmentation law for PFHE surfaces. This is characterized with the comparison to the vortex promoted heat transfer surfaces having an equal small channel at the same Reynolds numbers. Dubrovsky developed heat exchanger cores with three different fin surfaces. Out of the three, two of the surfaces are sort equilateral triangular and rectangular cross-sectional offset channels and the third surface possess isosceles triangular cross-sectional channels with transverse grooves which have projections along the direction of channel length.

Ranganayakulau et al. [10] analyzed the effect of non-uniform flow distribution of two-dimensional inlet fluids of both the cold and hot sides of the fluid in a cross-flow PFHE using finite element method. They developed mathematical equations for different mal-distribution models for various types of fluid flow, for the effectiveness of the exchanger and its declination due to the flow non-uniformity for all ranges of design and operating conditions. Kundu and Das [11] determined the optimum dimensions of the fin for the fin tube type heat exchangers. They found the maximum heat dissipation for any given value of thickness or pitch length for a fixed fin volume. Averous et al. (1999) presented a dynamic simulation for a brazed plate heat exchanger. Ranganayakulau et al. [12] analyzed the cross flow compact PFHE, accounting the combined effects of 2D heat conduction in the longitudinal direction through the wall of the exchanger, non-uniform flow of the inlet fluid and the temperature distribution using the finite element method. They observed that the declination of the thermal performance promotes the elimination of each other in the areas of higher NTU but promote each other in the areas of lower NTU, considering the heat conduction in the longitudinal direction, non-uniformity of the flow & the non-uniformity of the temperature. Picon-Nunez et al. [13] designed compact plate fin heat exchangers where main objective was the utilization of the pressure drop. Based on the performance of the volume performance index (VPI) the surface is selected. The PFHE sizing requires the specification of the type of the surface on each side of the streams that takes part in the process of heat transfer. So, the small exchanger volume was the basic design objective. They concluded that by utilizing the steam pressure drop & making highly thermal efficient heat transfer surfaces, this can be achieved. Wen & Li [14] analyzed the performance on the flow distribution of the fluid in the PFHE headers. They found that the fluid flow mal-distribution is very serious at the header length direction in the industrial used convectional headers due to poor header configuration. They also found that by using baffles the flow absolute parameter can be reduced. Kim et al. [15] investigated an experimental study for the heat transfer characteristics of a plate fin & tube fin heat exchangers by using the method of lumped capacitance based on liquid crystal thermography. Sahin et al. [16] proposed a model to know the flow behavior within plate fin & tube fin heat exchangers where they are made of two parallel plates having a single cylinder which is located between the plates. They did their experiment for duct height to cylinder dia. ratio of 0.365 with the *Re* value 4000-7500.

Peng and Ling [17] presented used of ANNs (artificial neural networks) for the prediction of pressure drop & heat transfer characteristics in the plate fin heat exchangers. The estimated result indicates that ANN models can be used for providing satisfactory estimations of both Colburn factor (j) & friction factor (f) in PFHEs. Li-Zhi Zhang [18] investigated the mal-distribution of the flow and the declination of the thermal performance in the cross flow air to air heat exchangers. Zhang et al. [19] developed a universal 3D distributed parameter model (DPM), for the evaluation & prediction of the steady behavior of PFHE. The model is able to satisfy the calculation for humid air in both wet & dry conditions. By using the DPM, they got the outlet temperature of the hot fluid of the exchanger under the wet condition is lower compared to the value that is obtained in the dry conditions. Wang et al. [20] experimentally studied the flow distribution of two-phase fluid in a PFHE under various operating conditions. They found that the flow distribution of the two-phase fluid is much more non-uniform & complex compared to that of the single phase flow. They also got that the non-uniformity distribution of the liquid phase declines with the reduction in the value of *Re gas* and *Re liquid*. And for the gas phase distribution uniformity reduces with *Re liquid* but increases with *Re gas*. Yousfei et al. [21] optimized a cross flow plate fin heat exchanger using an imperialist competitive algorithm (ICA). The minimization of the total annual cost & the total weight is the main objective. The length of the heat exchanger at the hot & cold side, height of the fin, frequency, thickness of the fin, strip length of the fin and the number of the hot side layer are the seven design parameters. Goyal et al. [22] presented a model for multi-stream plate fin heat exchanger for the applications in the cryogenic field, using finite volume analysis. They discretized the core of the heat exchanger both in the transverse as well as in the axial direction. The heat conduction that takes place axially through the metal matrix of the heat exchanger in those cases, heat leaks to the surrounding & the effects of the metal matrix conductivity are considered. Feru et al. [23] presented the modelling and model validation for a modular two-phase heat exchanger that recovers energy in heavy duty diesel engines. They developed this model for temperature and vapour quality production and for control design of the waste heat recovery system. This waste heat recovery system recovers energy both from the main exhaust line and from the exhaust gas circulation line.

Nagarajan et al. [24] developed a novel fin configuration for high-temperature ceramic plate fin heat exchanger using the 3D computational fluid dynamics (CFD) fluent code. They performed the numerical analysis for different types of fins & compare their results with the selected design. They studied the fluid flow, heat transfer pressure drop and the properties like Nusselt number, friction factor and Colburn factor for various fin configurations. Jeong et al. [25] developed a new shape of plate fin heat exchanger by creating holes & ceases on the fin. This is used in construction machinery under the poor environment with very high dust content & where the extraneous materials are produced. They comparatively analyzed the flow and the heat transfer phenomena on the heat transfer surface for the plate fin heat exchanger, louver fin heat exchanger and the newly proposed shape heat exchanger. Guo et al. [26] experimented for preventing the fluid leakage from the adjacent channel walls of the plate fin heat exchanger. For achieving the maximum heat transfer performance, they used a genetic algorithm (GA) for optimized along with the Monte-Carlo algorithm method for getting the suitable solution. Taler and Oclon [27] presented a method for the calculation of the mean value of thermal contact resistance for a plain fin & tube fin exchanger by using experimental measurements & CFD simulations. It is necessary to know the thermal contact resistance to predict the total gas side temperature difference. Manglik and Bergles [28] investigated on the thermodynamic & the hydraulic design tools for compact heat exchanger of rectangular offset strip fin and the effect of convection related to this. They reanalyzed the *j* and *f* data for the actual cores and also identified the asymptotic behaviour in the extreme laminar and fully turbulent flow regimes. They correlated the asymptotes obtained by the power law expressions in terms of the Reynolds number (Re) and by the dimensionless geometric parameters. Finally, they developed equations for *j* and *f* data for laminar, turbulent and transition flow regimes. Mishra et al. [29] developed an optimization technique based on genetic algorithm. The minimization of the entropy generation for a given heat duty under a specified space restrictions is the main objective. Bhowmik and Kwan-Soo Lee [30] used a steady state 3D numerical model for studying the pressure drop and heat transfer characteristics of an offset strip fin heat exchanger. Re *dh* ranged from 10 to 3500. They observed the fanning friction factor (*f*) variation and Colburn heat transfer factor (*j*) variation relative to *Re dh* . Then, they developed correlation for the *f* and *j* factors and analyzed the heat transfer and fluid flow characteristics of offset strip fins in the laminar, turbulent and the transient regions. Finally, they adopted three performance criteria i.e.,*(j/f)* , *(j/f) 1/3* and *jf*. Ismail et al. [31] found that the calculated dimensional performance of heat transfer surfaces (*j* and *f* vs. *Re*) strongly controls the thermodynamic design of compact heat exchangers. They studied the flow patterns of 3 types of offset fins and 16 types of wavy fins by using the fluent software.

Saad et al. [32] developed a correlation for the friction factor of the micro-channel having offset-strip fin geometry with single phase for laminar to the turbulent flow of air & water. Then, they did a comparison with 3D CFD simulations. Also by using a high-speed camera, they studied the distribution of pressure drop in the two-phase regime. Seara et al. [33] analyzed a titanium brazed PFHE with serrated fins in liquid-liquid heat transfer process experimentally. They conducted the experiment by taking the water on both sides of the exchanger & determined heat transfer characteristics and the pressure drop. They also developed a correlation to determine the convectional heat transfer coefficient of a single phase fluid as a function of Reynolds number. Yang and Li [34] numerically investigated the heat transfer coefficients and the flow friction coefficients for offset strip fins used in plate fin heat exchangers & compared it with well-validated 3D models. Based on the analysis by CFD simulations, they developed correlations for the general prediction of *j* and *f* factors which excellently correlate a variety of geometrical parameters with the comparison to the existing correlations. Their predictions for offset strip fins with different fin thickness over a broad range of blockage ratio. Suzuki et al. [35] studied the numerical and experimental analysis of the heat transfer and flow characteristics of a 2D flat plate arranged in a staggered manner used in mixed (free flow) convection region at low Reynolds number. Fischedick et al. [36] experimented on heat recovery of a ceramic PFHE being used for heat exchanger applications. Peng et al. [37] predicted the thermodynamic performance for longitudinal & transverse direction flow through the offset fins by a steady state, 3D numerical model.

III. CONCLUSION

Various correlations were developed by scientists for the Colburn factor (j) and Friction factor (f) in design of PFHE. Experimental analysis has been done to achieve desired design objectives and its result also compared with various correlations to understand real time situation. Also design and analysis has been done with help of 2D and 3D computer modelling and computation fluid dynamics (CFD) analysis in software to see deviation from correlations and experiments results also. It has been found from various experimental analysis and results that there has been deviation from correlation developed by various well known scientists like Maiti-Sarangi, Joshi-Webb and Manglik-Bergles etc. Maiti-Sarangi correlation of the Colburn factor (j) and Friction factor (f) results came near to experimental data than other scientist correlations. Deviation came to great extent if there is slight change in situation, so care must be taken before design of compact heat exchanger in cryogenics. There is very small margin in error in design of compact heat exchangers. Cost associated with cryogenic heat exchangers is very high, so one has to take care of all factors and situation in design of heat exchanger in cryogenics.

REFERENCES

[1] Fehle, R., J. Klas, and F. Mayinger. "Investigation of local heat transfer in compact heat exchangers by holographic interferometry." Experimental thermal and fluid science 10.2 (1995): 181-191.

[2] Ranganayakulu, Ch, K. N. Seetharamu, and K. V. Sreevatsan. "The effects of longitudinal heat conduction in compact plate-fin and tube-fin heat exchangers using a finite element method." International journal of heat and mass transfer40.6 (1997): 1261-1277.

[3] Sanaye, Sepehr, and Hassan Hajabdollahi. "Thermal-economic multi-objective optimization of plate fin heat exchanger using genetic algorithm." Applied Energy 87.6 (2010): 1893-1902.

[4] Rao, R. V., and V. K. Patel. "Thermodynamic optimization of cross flow plate-fin heat exchanger using a particle swarm optimization algorithm." International Journal of Thermal Sciences 49.9 (2010): 1712-1721.

[5] Hajabdollahi, Hassan, Mojtaba Tahani, and MH Shojaee Fard. "CFD modeling and multi-objective optimization of compact heat exchanger using CAN method." Applied Thermal Engineering 31.14 (2011): 2597-2604.

[6] Zhang, Feini, Jessica Bock, Anthony M. Jacobi, and Hailing Wu. "Simultaneous heat and mass transfer to air from a compact heat exchanger with water spray precooling and surface deluge cooling." Applied Thermal Engineering 63, no. 2 (2014): 528-540.

[7] Pingaud, H., Le Lann, J. M., Koehret, B., & Bardin, M. C. (1989). Steady-state and dynamic simulation of plate fin heat exchangers. Computers & Chemical Engineering, 13(4), 577-585.

[8] Müller-Menzel, T., and T. Hecht. "Plate-fin heat exchanger performance reduction in special two-phase flow conditions." Cryogenics 35.5 (1995): 297-301.

[9] Dubrovsky, E. V. "Experimental investigation of highly effective plate-fin heat exchanger surfaces." Experimental thermal and fluid science 10.2 (1995): 200-220.

[10] Ranganayakulu, Ch, K. N. Seetharamu, and K. V. Sreevatsan. "The effects of inlet fluid flow nonuniformity on thermal performance and pressure drops in crossflow plate-fin compact heat exchangers." International Journal of Heat and Mass Transfer 40.1 (1996): 27-38.

[11] Kundu, B., and P. K. Das. "Optimum dimensions of plate fins for fin-tube heat exchangers." International journal of heat and fluid flow 18.5 (1997): 530-537.

[12] Ranganayakulu, Ch, and K. N. Seetharamu. "The combined effects of longitudinal heat conduction, flow nonuniformity and temperature nonuniformity in crossflow plate-fin heat exchangers." International communications in heat and mass transfer 26.5 (1999): 669-678.

[13] Picon-Nunez, M., G. T. Polley, E. Torres-Reyes, and A. Gallegos-Munoz. "Surface selection and design of platefin heat exchangers." Applied Thermal Engineering 19, no. 9 (1999): 917-931.

[14] Wen, Jian, and Yanzhong Li. "Study of flow distribution and its improvement on the header of plate-fin heat exchanger." Cryogenics 44.11 (2004): 823-831.

[15] Kim, Ye Yong, Kui Soon Kim, Gi Ho Jeong, and Sooin Jeong. "An experimental study on the quantitative interpretation of local convective heat transfer for a plate fin and tube heat exchanger using lump capacitance method." International journal of heat and mass transfer 49, no. 1 (2006): 230-239.

[16] Sahin B., A. Akkoca, N. A. Ozturk and H. Akilli. "Investigatin of flow characteristics in a plate fin and tube heat exchanger model composed of single cylinder." International journal of heat and fluid flow 27, no. 3 (2006): 522-530.

[17] Peng, Hao, and Xiang Ling. "Optimal design approach for the plate-fin heat exchangers using neural networks cooperated with genetic algorithms." Applied Thermal Engineering 28.5 (2008): 642-650.

[18] Zhang, Li-Zhi. "Flow maldistribution and thermal performance deterioration in a cross-flow air to air heat exchanger with plate-fin cores." International journal of heat and mass transfer 52.19 (2009): 4500-4509.

[19] Zhang, Lina, Chunxin Yang, and Jianhui Zhou. "A distributed parameter model and its application in optimizing the plate-fin heat exchanger based on the minimum entropy generation." International Journal of Thermal Sciences 49.8 (2010): 1427-1436.

[20] Wang, Simin, Yanzhong Li, Jian Wen, and Yansong Ma. "Experimental investigation of header configuration on two-phase flow distribution in plate-fin heat exchanger." International Communications in Heat and Mass Transfer 37, no. 2 (2010): 116-120.

[21] Yousefi, M., A. N. Darus, and H. Mohammadi. "An imperialist competitive algorithm for optimal design of plate-fin heat exchangers." International Journal of Heat and Mass Transfer 55.11 (2012): 3178-3185.

[22] Goyal, Mukesh, Anindya Chakravarty, and M. D. Atrey. "Two dimensional model for multistream plate fin heat exchangers." Cryogenics 61 (2014): 70-78.

[23] Feru, Emanuel, Bram de Jager, Frank Willems, and Maarten Steinbuch. "Two-phase plate-fin heat exchanger modelling for waste heat recovery systems in diesel engines." Applied Energy 133 (2014): 183-196.

[24] Nagarajan, Vijaisri, Yitung Chen, Qiuwang Wang, and Ting Ma. "Numerical analysis of steady state and transient analysis of high temperature ceramic plate-fin heat exchanger." Nuclear Engineering and Design 277 (2014): 76-94.

[25] Jeong, Chan Hyeok, Hyung Rak Kim, Man Yeong Ha, Sung Wan Son, Jae Seok Lee, and Pan Yeong Kim. "Numerical investigation of thermal enhancement of plate fin type heat exchanger with creases and holes in construction machinery." Applied Thermal Engineering 62, no. 2 (2014): 529-544.

[26] Guo, Dongcai, Meng Liu, Liyao Xie, and Jun Wang. "Optimization in plate-fin safety structure of heat exchanger using genetic and Monte Carlo algorithm."Applied Thermal Engineering 70, no. 1 (2014): 341-349.

[27] Taler, Dawid, and Pawel Oclon. "Thermal contact resistance in fin and tube heat exchangers, determined by experimental data and CFD simulations." International Journal of Thermal Sciences 84 (2014):309-322.

[28] Manglik, R. M., & Bergles, A. E. (1995). Heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger. Experimental Thermal and Fluid Science, 10(2), 171-180.

[29] Mishra, Manish, P. K. Das, and Sunil Sarangi. "Second law based optimisation of crossflow plate-fin heat exchanger design using genetic algorithm." Applied thermal engineering 29.14 (2009): 2983-2989.

[30] Bhowmik, H., and Kwan-Soo Lee. "Analysis of heat transfer and pressure drop characteristics in an offset strip fin heat exchanger." International Communications in Heat and Mass Transfer 36.3 (2009): 259-263.

[31] Ismail, L. Sheik, Ch Ranganayakulu, and Ramesh K. Shah. "Numerical study of flow patterns of compact plate-fin heat exchangers and generation of design data for offset and wavy fins." International journal of heat and mass transfer 52.17 (2009): 3972-3983.

[32] Saad, Selma Ben, Patrice Clément, Caroline Gentric, Jean-François Fourmigué, and Jean-Pierre Leclerc. "Experimental distribution of phases and pressure drop in a two-phase offset strip fin type compact heat exchanger. " International journal of multi phase flow 37, no. 6, (2011): 576-584.

[33] Fernández-Seara, José, Rubén Diz, and Francisco J. Uhía. "Pressure drop and heat transfer characteristics of a titanium brazed plate-fin heat exchanger with offset strip fins." Applied Thermal Engineering 51.1 (2013): 502-511.

[34] Yang, Yujie, and Yanzhong Li. "General prediction of the thermal hydraulic performance for plate-fin heat exchanger with offset strip fins." International Journal of Heat and Mass Transfer 78 (2014): 860-870.

[35] Suzuki, K., E. Hirai, T. Miyake, and T. Sato. "Numerical and experimental studies on a two-dimensional model of an offset-strip-fin type compact heat exchanger used at low Reynolds number." International journal of heat and mass transfer 28, no. 4 (1985): 823-836.

[36] Schulte-Fischedick, Jan, Volker Dreißigacker, and Rainer Tamme. "An innovative ceramic high temperature plate-fin heat exchanger for EFCC processes." Applied Thermal Engineering 27.8 (2007): 1285-1294.

[37] Peng, Hao, and Xiang Ling. "Analysis of heat transfer and flow characteristics over serrated fins with different flow directions." Energy Conversion and Management 52.2 (2011): 826-835.