Numerical Investigation of Thermal Hydraulic Performance of Printed Circuit Heat Exchanger of Periodic Diamond Channel Shape

Ali M Aljelawy¹, Amer M Aldabbagh², Falah F Hatem³

¹,²,³ Department of Mechanical Engineering, University of Technology, Baghdad Iraq

¹engaljelawy@gmail.com

Abstract. One of the most recently important heat exchangers is the Printed circuit heat exchanger especially in the nuclear power plant and aerospace applications due to its very compact geometry and small print foot. This paper presents a 3D numerical investigation on the thermo-hydraulic performance of PCHE with new non-uniform channel design configuration. The new channel design is a rectangular cross section with repeated converging diverging sections or periodic diamond shape. The influence of three design parameters on the heat exchanger performance was studied and optimized, pitch length (p), length ratio (β) and the converging diverging angle (α). The computational models investigated in this study based on the operating conditions of the intermediate heat exchanger of very high temperature gas cooled reactor with helium as the working fluid under operating pressure of 3Mpa and inlet temperature of 800 K. The Reynolds number varied from 200 to 2000. Different Pitch lengths were used (1.59, 3.18, 6.36, and 12.73) mm, and different C-D angle (0, 4.5, 6, 7.5, 9, 10.5 and 12) and also different length ratios were used (0.2, 0.25 and 0.333). Three performance parameters were studied the Nusselt number, friction factor and the overall performance evaluation factor. Results show that the thermal performance enhanced with decreasing the pitch length and with increasing C-D angle and it was shown that this enhancement was found only at high Reynolds number above 1400. The best performance obtained at p=3.18, α=6 and β=0.25 based on the overall evaluation performance.

Keywords: printed circuit heat exchanger, mini channel fluid flow, heat transfer, Nusselt number, friction factor

1. Introduction

Printed circuit heat exchanger (PCHE) also called HEATRIC after the developer of this kind of heat exchanger is a high integrity high compact plate type heat exchanger. It has a unique design; it consists of many plates that are photo-chemically etched or pressed to form the flow passages configuration and then the plates stacked together and diffusion bonded (solid state joining) to form the block of heat exchanger. The flow passages formed as semicircular section because of the isotropic of etching process with different configurations. PCHE characterized by its high coefficient of heat transfer due to the high surface area to volume ratio and high pressure drop due to the small diameter. It can withstand high pressure about 600 bar.
with large temperatures ranging from cryogenic to 700°C [1]. Fluid flow inside PCHE can be parallel flow, counter flow, cross flow or a combination of these.

The thermal performance in PCHEs mainly enhanced passively by introducing a complex flow channels but, in the other hand an optimization must be done due to an expected increase in pressure drop. Previous studies on PCHEs focused on their thermal hydraulic performance characteristics to increase the heat transfer rate with pressure drop as low as possible. Both experimental and numerical studies have been conducted at this point of research study. Aneesh et al. [2] numerically investigated the thermal hydraulic performance of PCHE with straight flow channels with helium as a working fluid. The effect of operating condition, thermo-physical properties and three design parameters were studied (single and double bank, aligned and staggered and inserting dimples in to the flow channels). The results showed that the Thermal hydraulic performance is better in single bank than in double bank configuration, and inserting of dimple increase both heat transfer and pressure drop and this increase is higher with more dimple inserted, while the channels alignment does not have any effect on the performance. Chu et al. [3] experimentally investigated the performance of straight channel PCHE. The tests performed on super critical carbon dioxide and water (SCO2-water) with different SCO2 operating pressure. The results reveal that SCO2’s heat transfer capability exceeds that of water, even though they both operate under the exact mass flow rates and pressure conditions. The work of S.Lee and Kim [4] was done to help establish how effective a new design is. An additional thin plate was added between the hot and cold channels. Additionally, the analysis of the overlap of hot and cold regions was done. The proposed design outperforms the reference design in terms of thermal performance. Taylor et al. [5] numerically investigate the thermal-hydraulic performance of PCHE. The effect of two design parameters namely the ellipse aspect ratio and channel angle of zigzag flow channel pattern were studied. The results show that the best effectiveness of PCHE obtained at channel angle of 110. And the effectiveness increases with increasing aspect ratio of cold channel. while the friction factor increases with increasing the aspect ratio. Baek et al. [6] experimentally investigated the thermal-hydraulic performance of PCHE for use in the cryogenic temperature region, with helium as the working fluid at cryogenic temperatures. The study also focused on the effect of axial conduction on the thermal performance. They showed that The axial conduction has a major influence in lowering the thermal performance of PCHE in cryogenic environment and its effect increases with increasing temperature due to increase in thermal conductivity. Baik et al. [7] conducted numerical and experimental study on the design and operating conditions of PCHE of zigzag channel shape in supercritical CO2 cycle. Moreover a one dimensional. The result cleared that the sharp corner channel showed 40–65% larger pressure drop compared to the realistic round corner channel due to the occurrence of reverse flow. H. Kim et al. [8] experimentally investigated The thermal-hydraulic performance of wavy PCHE in KAIST helium test cycle. Also 3-D numerical simulation using FLUENT software was performed to obtain the local Nusselt number and to compare with the experimental results. It was obvious that Nusselt number increases with increasing Reynolds number while friction factor decreases with increasing Reynolds number. H. Kim and No [9] performed experimental and numerical investigation for the thermal hydraulic performance of PCHE with helium-water working fluids in horizontal and vertical arrangement. Experiments carried out in laminar region. S. G. Kim et al. [10] performed CFD analyses to examine the thermal hydraulic performance of wavy PCHE in S-CO2 power cycle. S. L. K. Kim [11] conducted Comparative study about the effect of various channel cross-sectional shapes on zigzag PCHE performance using 3-D RANS. Four different cross-sectional shapes of channel (circular, semicircular, rectangular, and trapezoidal). For these cases, the rectangular channel exhibits the best thermal performance, but the worst hydraulic performance. In an effort to improve heat transfer and friction loss characteristics, three scientists, S. Lee, Kim, and Kim[12], carried out a numerical optimization study on double-faced type zigzag flow channels of a printed circuit heat exchanger utilizing 3D RANS analysis. Non-dimensional factors such as the fillet radius, wavelength, and wave height/height of a wave were selected to model the hydraulic diameter of the channels. It was shown that double face reference channel shows higher effectiveness but a similar friction factor of single face one.
S. Lee and Kim [13] determine if three-dimensional RANS simulations of the Arc-shaped ribs of a cooling wavy channel will boost heat transfer using numerical simulation by performing a numerical investigation. Comparing two design parameters with two different geometric approaches (the ratios of the pitch and depth of the ribs to the hydraulic diameter of the channel). In addition to the previously mentioned specifications, the new design offers improvements in both thermal performance and pressure drop when compared to the reference design without ribs. Yoon et al. [14] investigated numerically the performance of PCHE working with supercritical CO2/ eutectic lead-lithium. The heat exchanger plates made with an airfoil shaped fin. Optimization of the airfoil shapes fins arrangement carried out in terms of pressure drop and heat transfer. The results show that the minimum relation \(_{P/Q}\) occurs with the largest distance between airfoils. Cui et al. [15] numerically investigated the performance of PCHE using two novel air-foil fins based on NACA 0020 with SCO2 as the working fluid. The staggered and aligned fins arrangement were considered. The results show that one of the two fins gives a better comprehensive performance than that of NACA 0020 which gives higher \(j\) factor and lower pressure drop than NACA 0020 due to the thinner boundary layer. The staggered arrangement of fins reduces the boundary layer effect and increase the heat transfer. Ngo et al. [16] conducted an experimental study to investigate the thermo-hydraulic performance of a new developed microchannel heat exchanger (MCHE) with S-shaped and zigzag fins. By comparing the pressures involved with the resulting flow for different kinds of fin shapes, the Nusselt number increases with zigzag fins (in the 24- to 34% range) while the pressure drop increases 4-5 times over, all depending on Reynolds number [20, 21].

In this study, computational fluid dynamics (CFD) models were used to analyze the thermal hydraulic performance of periodic diamond channel heat exchangers. Three channel design factors were evaluated and optimized for heat exchanger performance, pitch length (\(p\)), length ratio (\(\beta\)) and the converging diverging angle angle (\(\alpha\)).

2. Numerical model and method

2.1. Computational Models

It is well known that there are two methods used to enhance heat transfer; the active method that requires an external power addition such as vibration, the second method is the passive method which is not required any external power addition such extended surfaces disturbance and swirl generators (twisted tape, twisted tube, etc.). In the present work a periodic converging diverging channel used to disturb the flow with various design parameters (inlet angle (\(\alpha\)), length ratio (\(\beta\)) and pitch length (\(p\))). Where \(\beta\) is the converging section length divided by the entire length of the periodic section.

The channel has a rectangular cross section. The full geometry of PCHE which shows channels configuration shown in figure 1, and the periodic section of these channels shown in figure 2. It is well known that the channels of this heat exchanger usually have a semi circler cross section due to the isotropous of chemical etching technique used, but we proposed a different technique to produce the flow channels which is by the electric discharge machines (EDM), it is a useful technique for machining mini or micro parts,
Figure 1. Full PCHE building block geometry

Figure 2. Periodic channel section

2.2. Numerical method

A 3-D numerical simulation was done using Ansys Fluent 18. The assumptions used here are steady-state, laminar flow, uniform velocity and negligible viscous dissipation and radiation effects. In order to reduce the computational cost, a single channel with constant wall heat flux will be simulated with temperature dependent properties of Helium which is the working fluid, the properties of Helium obtained from NIST web book [17].

The segregated solver is used for solving the governing equations with double precision for higher accuracy. For convergence issue, residual is set at $10^{-4}$ for continuity and $10^{-6}$ for momentum and energy, and the quantities of interest are monitored. A structured grid of hexahedron cells is used with finer mesh near the wall with 5 prism layers to catch the boundary layer and reduce the mesh size as shown in figure 3. A grid independent study performed for the maximum Reynold number of 2000 to obtain the optimum mesh size as shown in table 1.

Figure 3. Mesh of PCHE channel analysis model
Table 1. Mesh independent test results

| Cell number | Nu     | f       |
|-------------|--------|---------|
| 915200      | 7.800621 | 0.015205 |
| 1806580     | 8.203682 | 0.015593 |
| 2779760     | 8.319968 | 0.015729 |

To insures the validity of the numerical work, a comparison was made with the experimental data of zigzag channel PCHE presented by Chen et al. [18] as shown in figure 4 and figure 5. Also a reduced scale model was used of single channel with constant wall heat flux it was shown a good agreement with the experimental data published. The results show a little deviation and this is not odd.

2.3. Data reduction

The Nusselt number, friction factor and the overall performance evaluation factor (η) are calculated from fluent data as:

\[ \text{Nu} = \frac{h d_h}{k_f} \]
\[ h = \frac{q''}{T_{\text{bulk}} - T_{\text{wall}}} \]
\[ f_{\text{Fanning}} = \frac{1}{4} \frac{D h}{l} \frac{2}{\rho v^2} \]
\[ \eta = \left( \frac{\text{Nu}}{\text{Nu}_s} \right) \left( \frac{f}{f_s} \right)^{1/3} \]

Where \( q'' \) is the average heat flux, \( T_{\text{wall}} \) is the area average wall temperature and, \( T_{\text{bulk}} \) is the average helium bulk temperature which is the mass weighted average temperature. \( \text{Nu}_s \) represent the Nusselt number and friction factor for smooth rectangular channel, \( d_h \) is the hydraulic diameter which is the equivalent diameter along the channel, also it can be calculated as [19]:

\[ d_h = \frac{4V}{A_s} \]
3. Results and discussion
There are three main parameters of interest, Nusselt Number (Nu), friction factor (f), and the overall performance evaluation factor (η).
3.1. Nusselt number

Figure 6 and figure 7 indicate the Nusselt against Reynold number for various pitch lengths and the converging angles. It turns out from figure 6 that for the same inlet angle of $\alpha = 7.5^\circ$ Nusselt number increases with the decrease in pitch length at the same Reynolds number until it reaches a value which is ($p = 3.1825$) which after this value, the Nusselt number begin to decrease. Figure 7 show that Nusselt number increases with the increase in converging diverging angle, also it reaches a value at which Nusselt begin to decrease, this angle value differs for each pitch length. The reason behind that inversion in behavior is the separation of the flow with the smaller pitch length and with the wider opening of converging diverging angle which will increase the thermal resistance by shadowing the heat transfer area as it cleared in velocity contour in figure 12. And it is obvious from the velocity contour that by decreasing the length ratio ($\beta$) the separation region reduces as shown in contour (f) in figure 12. The local Nusselt number may give us an indication of the thermal enhancement through the channel length as shown in figure 8. The thermal performance enhancement appears in the high Reynolds range, while at low Reynolds range the performance gives an adverse behavior.

Figure 6. Nusselt number versus Reynolds number for different pitch lengths.
Figure 7. Nusselt number versus Reynolds number for different C-D angle.

Figure 8. Local heat transfer coefficient along the channel for Re=2000.

3.2. Friction factor
Figure 9 and figure 10 show that the friction factor vs Reynolds number for various pitch length and different converging diverging angle. It appears that the friction factor rises with the decrease in pitch length as shown in figure 9, while it falls with increasing C-D angle as shown in figure 10. Figure 11 shows the local friction factor for one of our cases to show the behavior along the channel length and through the converging diverging sections. Also, it is cleared that the separation increases the friction losses.
Figure 9. Friction factor versus Reynolds number for different pitch length

Figure 10. Friction factor versus Reynolds number for different C-D angle.
Figure 11. Local friction factor along the channel length

Flow direction

- **a)** $P = 12.73$ mm, $\alpha = 6$, $Re = 2000$
- **b)** $P = 12.73$ mm, $\alpha = 9$, $Re = 2000$
- **c)** $P = 12.73$ mm, $\alpha = 7.5$, $Re = 2000$
3.3. Overall performance evaluation factor ($\eta$).

The overall performance evaluation factor can be used for better comparison because it takes account of both thermal performance and pumping power. Figure 13 shows that the overall performance of all cases. It is obvious that $p=3.1825$ with $\alpha=9$ gives the best performance at all Reynolds number range.

**Figure 12.** Velocity contour for different C-D channels.

**Figure 13.** Overall performance evaluation factor Reynolds number for all cases.
4. Conclusion
3D numerical study was performed to investigate the thermal hydraulic performance of a PCHE with new non-uniform channel configuration which consist of repeated converging diverging sections. Three geometric parameters were studied pitch length, length ratio ($\beta$) and converging diverging angle ($\alpha$), and three performance parameters were obtained which are the Nusselt number, friction factor and the overall performance evaluation factor. The results show a good enhancement in thermal performance with reducing the pitch length and increasing C-D angle and the best performance have been obtained at $p=3.1825$ mm $\beta=0.25$ and $\alpha=6$. The main reason behind the enhancement is the disruption of the boundary layer and the good mixing induced in the fluid flow due to the velocity oscillation.

References
[1] Thulukkanam K, Heat Exchanger Design Handbook, 2nd Edition. 2013.
[2] Aneesh A M Sharma ASrivastava AVyas K Nand Chaudhuri P, “Thermal-hydraulic characteristics and performance of 3D straight channel based printed circuit heat exchanger,” vol. 98, pp. 474–482, 2016.
[3] Chu WLi XMa T Chen Yand Wang Q, “International Journal of Heat and Mass Transfer Experimental investigation on SCO 2–water heat transfer characteristics in a printed circuit heat exchanger with straight channels,” Int. J. Heat Mass Transf., vol. 113, pp. 184–194, 2017.
[4] Lee S M and Kim K Y, “Thermal performance of a double-faced printed circuit heat exchanger with thin plates,” J. Thermophys. Heat Transf., vol. 28, no. 2, pp. 251–257, 2014.
[5] Lee S M and Kim K Y, “A parametric study of the thermal-hydraulic performance of a zigzag printed circuit heat exchanger,” Heat Transf. Eng., vol. 35, no. 13, pp. 1192–1200, 2014.
[6] Baek SKim J Jeong Sand Jung J, “Development of highly effective cryogenic printed circuit heat exchanger (PCHE) with low axial conduction,” Cryogenics (Guildf.), vol. 52, no. 7–9, pp. 366–374, 2012.
[7] Baik SKim S GLee Jand Lee J I, “Study on CO 2–water printed circuit heat exchanger performance operating under various CO 2 phases for S-CO 2 power cycle application,” Appl. Therm. Eng., vol. 113, pp. 1536–1546, 2017.
[8] Kim I HNo H CLee J Iand Jeon B G, “Thermal hydraulic performance analysis of the printed circuit heat exchanger using a helium test facility and CFD simulations,” Nucl. Eng. Des., vol. 239, no. 11, pp. 2399–2408, 2009.
[9] Kim I H and No H C, “Thermal hydraulic performance analysis of a printed circuit heat exchanger using a helium-water test loop and numerical simulations,” Appl. Therm. Eng., vol. 31, no. 17–18, pp. 4064–4073, 2011.
[10] Kim S GLee Y Ahn Yand Lee J I, “CFD aided approach to design printed circuit heat exchangers for supercritical CO2 Brayton cycle application,” Ann. Nucl. Energy, vol. 92, pp. 175–185, 2016.
[11] Kim S L K, “Comparative study on performance of a zigzag printed circuit heat exchanger with various channel shapes and configurations,” pp. 1021–1028, 2013.
[12] Lee SKim Kand Kim S, “Multi-objective optimization of a double-faced type printed circuit heat exchanger,” Appl. Therm. Eng., vol. 60, no. 1–2, pp. 44–50, 2013.
[13] Lee S and Kim K, “International Journal of Thermal Sciences Multi-objective optimization of arc-shaped ribs in the channels of a printed circuit heat exchanger,” Int. J. Therm. Sci., vol. 94, pp. 1–8, 2015.
[14] Fernández I and Sedano L, “Design analysis of a lead – lithium / supercritical CO 2 Printed Circuit Heat Exchanger for primary power recovery,” Fusion Eng. Des., vol. 88, no. 9–10, pp. 2427–2430, 2013.
[15] Cui XGuo JHuai XCheng KZhang Hand Xiang M, “Numerical study on novel airfoil fins for printed circuit heat exchanger using supercritical CO2,” Int. J. Heat Mass Transf., vol. 121, pp. 354–366, 2018.

[16] Ngo T LKato YNikitin Kand Ishizuka T, “Heat transfer and pressure drop correlations of microchannel heat exchangers with S-shaped and zigzag fins for carbon dioxide cycles,” Exp. Therm. Fluid Sci., vol. 32, no. 2, pp. 560–570, 2007.

[17] “Thermophysical Properties of Fluid Systems.” https://webbook.nist.gov/chemistry/fluid/ (accessed Apr. 16, 2020).

[18] Chen MSun XChristensen R NSkavdahl IUtgikar Vand Sabharwall P, “Pressure drop and heat transfer characteristics of a high-temperature printed circuit heat exchanger,” Appl. Therm. Eng., vol. 108, pp. 1409–1417, 2016.

[19] Hesselgreaves J ELaw Rand Reay D A, “Chapter 1 - Introduction,” J. E. Hesselgreaves, R. Law, and D. A. B. T.-C. H. E. (Second E. Reay, Eds. Butterworth-Heinemann, 2017, pp. 1–33.

[20] Ronak Ali et al 2020 J. Phys.: Conf. Ser. 1530 012156.

[21] B. Duraković and A. Cosic, “Impact of quality and innovation strategies on business performance of Bosnian B2B and B2C companies”, Sustainable Engineering and Innovation, vol. 1, no. 1, pp. 24-42, 2019.