NUMERICAL ANALYSIS OF THERMAL PERFORMANCE OF HEAT EXCHANGER
Different Plate Structures and Fluids

by

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Due to compact size, high power density, low cost and short construction time, the small modular reactors are considered as one of the candidate reactors, in which the power generation system is important with a compact heat exchanger for modular construction. Therefore, the effect of plate structure and nature of the working fluid on the thermal performance of plate heat exchanger are analyzed for the design of compact and efficient heat exchanger. The heat transfer rate, temperature counters, velocity vectors, and pressure drop have been optimized and investigated using FLUENT. The Nusselt number has been calculated for the corrugated and flat plate heat exchanger to validate the convective heat transfer. The numerical results are agreed well with correlation within deviation of ~5-7%. The performance of heat exchanger can be improved by controlling the mass-flow rate, and temperature of working fluid. The corrugation plate heat exchanger increases the heat transfer rate 20% and effectiveness 23%, respectively, as compare to flat plate heat exchanger when the working fluid is water. In the case of air, heat transfer rate, and effectiveness are about 10% and 9%, respectively. The results show that the corrugated plate heat exchanger is more effective than the flat plate heat exchanger because corrugation pattern enhances the turbulence of fluids, which further increase heat transfer rate and coefficient. The selection of the working fluid and structure of the plate must be considered carefully for efficient and compact design of heat exchanger.

Key words: *heat transfer area, CFD, plate heat exchanger, corrugated structure thermal hydraulics*

Introduction

Generation-IV (GEN-IV) reactors are also known as the advanced reactors and have ability to produce marvelous amount of thermal energy at higher temperature [1, 2]. An accelerator driven-subcritical (ADS) system is considered for construction in China because of its extraordinary potential for nuclear energy sustainability and waste transmutation. Therefore, Chines Academy of Sciences (CAS) launched the Future Advanced Nuclear Fission Energy (FANFE) – ADS Transmutation system [3, 4]. The Institute of Nuclear Energy Safety Technology, CAS [5] proposed the China LEAd-based Reactor (CLEAR), which was chosen as a model for ADS and this is mainly for the key technology R&D for GEN-IV lead-based reactor [6, 7].

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The small modular reactors (SMR) are the future of the nuclear power generation systems. The lead-based reactor with safety and high power density are considered as a promising candidate reactor for SMR. The power generation system of the SMR is important with compact and promising energy recovery device for modular construction. In power generation system, the heat is transferred from reactor core to power generation system through energy recovery device by using the working fluid.

The heat exchanger (HE) is key component of energy recovery devices [8-11]. Rios-Iribe *et al.* [12] mentioned two major classifications of the HE *i.e.* indirect contact-type and direct contact-type. If fluids remain separate, no mixing of the fluid and heat is transferred from the separating wall between fluids then it's called indirect type HE. In direct type, the heat is transferred through partially or completely mixing of the fluid. The most probably used system of indirect contact type is plate heat exchanger (PHE) [13]. The PHE are popular due to their low weight, compact size, easy handling, high thermal efficiency, easy to be clean and high thermal performance as compared to other conventional types of HE [14-19].

The flat structure provides less turbulence and heat transfer area. Therefore, a concept of the corrugated pattern was generated to enhance the heat transfer rate and area. The PHE are excessively utilized in engineering applications such as power recovery, power generation system, refrigeration, air conditioning, ventilation, food and chemical industry, *etc.* [6, 20-23]. The geometrical properties are adversely effects on the thermal performance of HE and it is difficult to analyze the flow inside such complex structure.

Durmus *et al.* [24] experimentally evaluated the energy loss for flat and asterisk PHE at Reynolds number ranges from 50 to 1000 and derives some relation which are applicable only for those structures. Dvorak [25] numerically analyzed the effectiveness and pressure drop for recuperative of zero thickness. Pressure drop enhanced with thickness of the plate. Tiwari *et al.* [14] numerically and experimentally explained the performance of nanofluids, *e.g.* CeO_2 and Al_2O_3, with chevron, nanofluids enhanced the performance of HE. Gherasim *et al.* [26, 27] experimentally investigated the frictional factor and Nusselt number in a HE then extended it numerically for the assessment of laminar and two equation turbulent models by comparing the simulation results with the experimental ones. The deposition of unwanted material is easy to be clean which decreased the heat transfer rate [28-30]. Pantzali *et al.* [31] explained experimentally and numerically the effect of nanofluid as working fluid for a miniature PHE. The CFD is helpful in designing, optimization, and solving the mathematical equation [32-34].

Literature is lacked of quantitative and specifically analysis of structural performance and about selection of the working fluid for the compact HE which can be used in the power generation system of SMLR. Therefore, it is necessary to analyze the impact of working fluid and structure of the PHE on thermal performance and hydraulics characteristics of PHE, and to enhance the acknowledgment about performance analyses of thermos-hydraulics devices. The corrugation angle 21.801° was chosen for the corrugated structure to evaluate the impact of smaller angle on thermal performance of corrugation structure of the PHE for the better performance. Flat and corrugated structures of PHE were selected with water and air as working fluid to analyze the thermal performance, pressure drop, effectiveness and existence of heat transfer phenomenon across the structure of PHE using CFD code FLUENT. The convective heat transfer for corrugated and flat PHE were calculated using FLUENT and correlation to validate the model and to make sure the calculations. This work can be used for the design and optimization of efficient heat recovery device for the lead-based SMR power generation systems.

Geometrical description

Plates with different dimensions and designs are available in market. The main objective to provide the corrugation is to increase the effectiveness and strength of plate to within stand differential pressures between plates. The geometrical dimensions of HE are $L_v L_w = 1.3 \cdot 0.7$ m and thickness of plate is 0.0007 m. The L_w is actual horizontal length of the plate and L_v is vertically distance between two ports. All parameters were designed according to limitation of the design [35].

Table 1. Dimensions of corrugated and flat PHE

	Corrugation PHE	Flat PHE
Length, L_v, [m]	1.3	1.3
Width, L_w, [m]	0.7	0.7
Thickness [m]	0.0007	0.0007
Port diameter, D_p, [m]	0.2	0.2
Pitch of corrugation, p, [m]	0.01	–
Corrugation angle [°]	21.801	–
Depth of corrugation, b, [m]	0.002	–

The geometry of the flat and corrugated PHE was created using ICEM in order to be exported in FLUENT for further processing. The geometrical dimensions of the flat and corrugated structures of PHE are given in tab. 1 and their structures are shown in fig. 1.

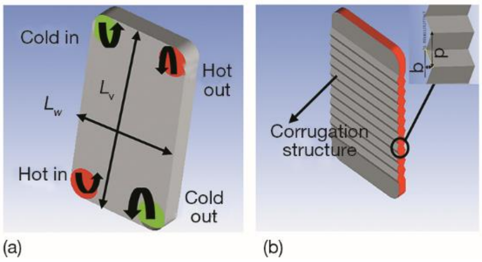


Figure 1. Structural views of PHE; (a) flat PHE and (b) corrugated PHE with 21.801°

Numerical method

Governing equations and mathematical model

Navier-Stokes equations involving discretized solution set of partial differential equations are the basics of CFD [36]. The PHE is a steady flow heat transfer device in which fluid is flow over surface. Flow has very complex structure because of the rotation/swirl and stream line curvature [37-39]. It is very important to note that turbulence occurs at low Reynolds number and flow is turbulent for lower values of velocity [40]. The *k-ε* standard model is suitable for 3-D simulation of heat transfer devices with standard wall function [18]. Steady-state models are based on conservation of energy, momentum and continuity equations [41]:

$$\frac{\partial(\rho \bar{u}_i)}{\partial x_i} = 0 \tag{1}$$

$$u_j \frac{\partial(\rho \bar{u}_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \tag{2}$$

$$c_p u_j \frac{\partial(\rho T)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(k+k_t)\frac{\partial T}{\partial x_j}\right] \tag{3}$$

where ρ is the density, p – the pressure, T – the temperature, C_p – the specific heat, k – the turbulence kinetic energy, and u – the velocity of fluid. Reynolds, Re, and Prandtl, Pr, numbers are dimensionless. These quantities are most commonly used in the calculation of momentum and heat transfer process. The Re relationship is:

$$\text{Re} = \frac{\rho u d_\text{e}}{\mu} \tag{4}$$

where μ is the viscosity of fluids, d_e – the equivalent diameter, and u – the average velocity. Momentum to thermal conductivity of the fluid ratio is Prandtl number. In eq. (5) C_p is the specific heat constant and K_f is the thermal conductivity of the fluid.

$$\text{Pr} = C_p \frac{\mu}{K_\text{f}} \tag{5}$$

The heat transfer rate, Q, of the working fluid can be calculated:

$$Q = \dot{m}_h C_{p,h}(T_{hi} - T_{ho}) = \dot{m}_c C_{p,c}(T_{co} - T_{ci}) \tag{6}$$

Pressure drop is calculated by using following mathematical expression:

$$\Delta P = P_\text{in} - P_\text{out} \tag{7}$$

If the fluids have the same mass-flow rate and specific heat capacities $C_{p,h} = C_{p,c}$, then the effectiveness or efficiency of HE is given by [1]:

$$\varepsilon = \frac{T_{hi} - T_{ho}}{T_{hi} - T_{ci}} \tag{8}$$

Grid independency

For making the good use of available computing facilities and to simplify the numerical mode two fluid bodies and one solid body was considered as complete HE. Three zones were generated in ICEM (2 fluid zones and 1 solid zone) and were interconnected with each other to generate the mesh. Unstructured mesh was generated in ICEM, and boundary layer grids were meshed in fluid domain near to structural wall, mesh smoothening was high and set the overall skewness in acceptable range of 0.90 as shown in fig. 2.

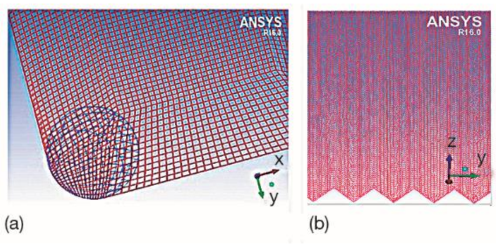


Figure 2. Meshes for flat and corrugated PHE; (a) flat PHE and (b) corrugated PHE

The quality of numerical simulation is based on the grid independency test. Therefore, the temperature of hot air at outlet of PHE was calculated across different numbers of mesh elements for both flat and corrugated PHE as shown in fig. 3 for the validation of the mesh model. Mesh model of PHE shows grid independency after 232905 and 153970 number of mesh elements for flat and corrugated structure of PHE, respectively. There is no much variation in temperature after 232905 and 153970 number of elements for flat and corrugation structures.

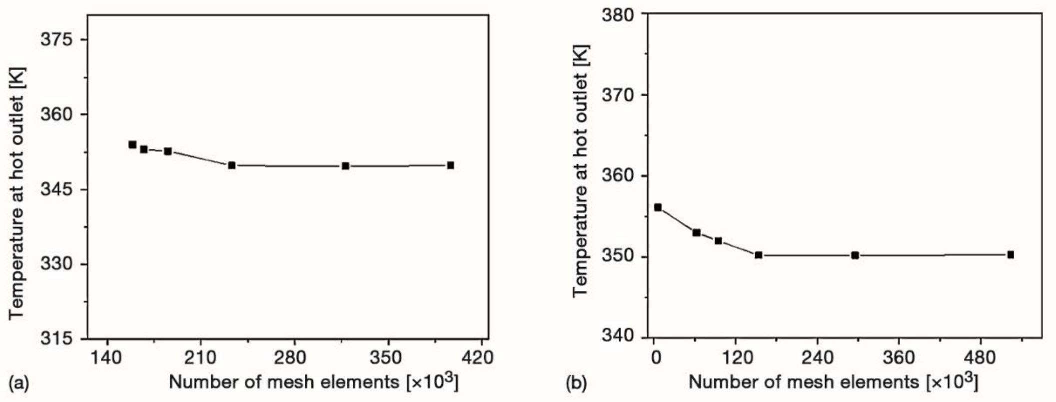


Figure 3. Grid dependency test; (a) flat PHE and (b) corrugated PHE

Thermal conditions

The CFD technique with FLUENT was used for solving the governing equations with some assumption:
– Steady-state condition applied for operation of PHE.
– The surfaces for heat transfer were considered free from fouling.
– Flow was equally distributed and there was no mal-distribution of flow.
– Outer walls were assumed to be adiabatic (*i.e.* no heat could enter and loss from system).

Boundary conditions

Inlet: the velocity inlet boundary condition was defined at the inlets of PHE for hot and coolant fluid. Their input values are listed in tab. 2. The system was operated at atmospheric pressure and turbulence intensity for every simulation was calculated [27]:

$$I = 0.16.\mathrm{Re}^{(-1/8)} \tag{9}$$

While inlet temperature for cold and hot sides was chosen 25 °C and 250 °C, respectively. In case of air, the inlet temperature for coolant and hot sides was chosen 25 °C and 100 °C, respectively. From the literature and recent studies provided that, run simulation with phase change of fluid and the results evaluated are not up to mark [36]. Therefore, the temperature of hot water was used equivalent to temperature of the pressurized water.

Outlet: At the two outlet pressure outlet boundary condition was applied with static pressure. The outlet temperature was defined as average of both fluids inlets temperature.

Wall: All outer surfaces were defined as wall and there was no heat transfer between surfaces and outer environment. The hydraulic diameter meter for corrugation and flat plate was 0.004 m and 0.002 m.

The FLUENT is based on finite volume method discretization technique, involving the steady-state of discrete approximation of surface. The thermophyscial properties of the water and air as working fluid were assigned. Convergence criteria was used for the optimization and precision of the result. In the solution method, SIMPLE scheme was used for coupling. Default the setting for solution control and solution method, changed the relative residual to 10^{-6} for energy momentum and continuity. Relaxation factor for pressure 0.3, for energy 1, and for momentum 0.7 was chosen, respectively. Default setting for the solution hybrid initialization method was chosen for solution initialization and then to run the iterations about 12000-15000 in order to converge the solution. Each mesh case averagely took 14-15 hours in order to get the converged solution with super computer. The solution must be converged for the precise calculation of the outlet parameters.

Table 2. Inlet velocities of HE [ms^{-1}]

Serial number	Cases I, III	Cases II, IV
1	0.00201	0.0292
2	0.00402	0.0584
3	0.00603	0.0876
4	0.00804	0.1169
5	0.009999	0.1461

Results and discussions

Four cases were considered in this work as listed in tab. 3. The effectiveness, pressure drop, heat transfer rate, outlet temperature of hot and coolant fluids, velocity and Nusselt number were calculated from CFD. Mass-flow rates for both hot and coolant fluids were the same.

Table 3. Working fluid and types of HE

HE	Hot side	Coolant side	Case no.
Flat PHE	Water	Water	I
	Air	Air	II
Corrugated PHE	Water	Water	III
	Air	Air	IV

Effect of structure and working fluid on effectiveness

The effectiveness of the HE is depended on the heat transfer rate, which is in relation with temperature difference of working fluid. Therefore, the effectiveness is selected as a parameter for the evaluation of CFD results with different structures and working fluids. The influence of mass-flow rate of fluids on the heat transfer rate through plates is shown in figs. 4 (a) and 4(b). The heat transfer rate is based on the temperature difference, specific heat, and mass-flow rate of the fluid according to eq. (6). Therefore, the small variation in mass-flow rate will increase the heat transfer rate since temperature difference will also change likely due to decrease in the outlet temperature. As in the case of corrugation structure, the plate heat transfer area is increased due to corrugation pattern. Khairul *et al.* [42] evaluated the thermal hydraulic performance of corrugated PHE and concluded that heat transfer rate was enhanced by enhancing the volume flow rate of the nanoparticle.

At the same length of plate, the heat transfer rate of the HE with corrugation structure is higher than that of flat structure because corrugation pattern increased the heat transfer area of the plate as shown in figs. 4(a) and 4(b). At the same value of heat transfer rate, the fluid with lower specific heat will produce the higher temperature difference and heat required

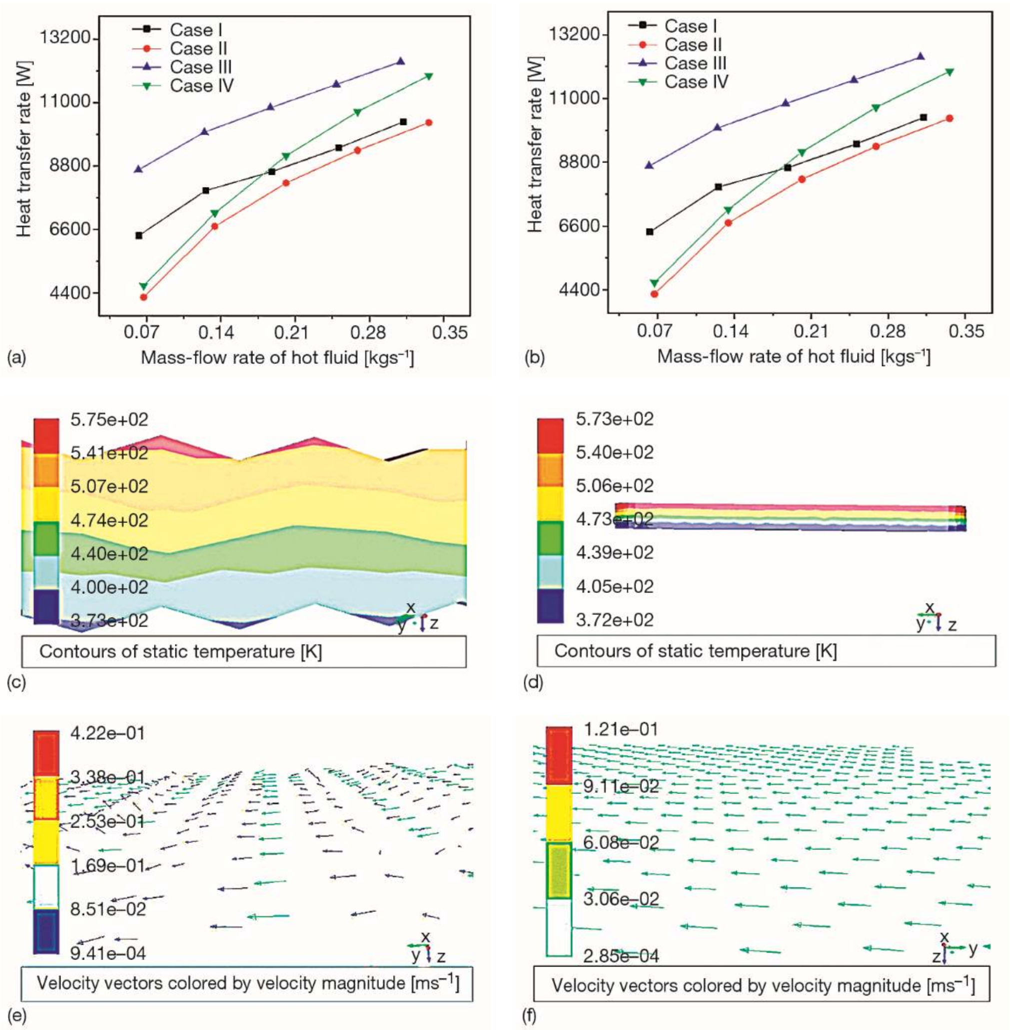


Figure 4. Effect of mass-flow rate on Q, temperature counters, and velocity vectors; (a) coolant fluid, (b) hot fluid, (c) temperature contours for corrugated structure, (d) temperature contours for flat structure, (e) velocity vectors for corrugated structure, and (f) velocity vectors for flat structure (*for color image see journal web site*)

to raise unit temperature of unit mass of the working fluid. Therefore, a high heat transfer rate was observed for the corrugated PHE with water as compared to air. The entropy generation on coolant side was 3% more than flat PHE in case of corrugation PHE, which increased the heat transfer of coolant fluid. The temperature difference for both hot and coolant fluids will be decreased with the increase of the mass-flow rate and it changes the heat transfer rate. The temperature difference is more for corrugated plate and less for flat plate, whether working fluid is water or air, because corrugation pattern increases the turbulence. While, heat flux for the corrugated plate is less in comparison with flat plate because it involves the heat transfer per unit area. The heat transfer rate of corrugated plate is 20% more than that of flat plate with water as working fluid, while, in case of air it is about 10% and this change is because of different velocities and inlet temperatures of the fluids. Also, the specific heats of both fluids are different from each other.

The temperature counters and velocity vectors of the fluid across the corrugated and flat structures of the PHE are shown in figs. 4(c)-4(f) for better understanding of the heat transfer characteristics of the working fluid along the length of structure. The variation in the temperature distribution along the plate is shown in figs. 4(c) and 4(d). The heat is transferred through plate due to conduction and convection heat transfer between solid plate and fluid on each side. The colors of temperature contours are changed as the heat is transferred along the plate. The change in temperature is more for the corrugated structure, therefore heat transfer rate of corrugation structure is higher than that of flat structure. The velocity decreases as the fluid is flow over the corrugation patteren. It can be seen from figs. 4(e) and 4(f) that as the fluid is moving in forwared toward inclination, its velocity is decreased. When fluid comes down on other side its velocity will increase. While across the flat plate velocity distributation is very smooth as shown in fig. 4(f). This variation in velocity of corrugated PHE affects the heat transfer rate because of turbulence.

The performance evaluation of HE depends on the effectiveness [43] and variation in the effectiveness with the mass-flow rate of coolant is shown in fig. 5. The effectiveness is the ratio of hot or cold fluid temperature difference to the maximum temperature difference of the fluids at the same mass-flow rate. The effectiveness of corrugated plate is more than the flat plate because of high temperature difference at the outlet and high heat transfer rate across the plate. The effectiveness is decreased with the increase of mass-flow rate [25, 43].

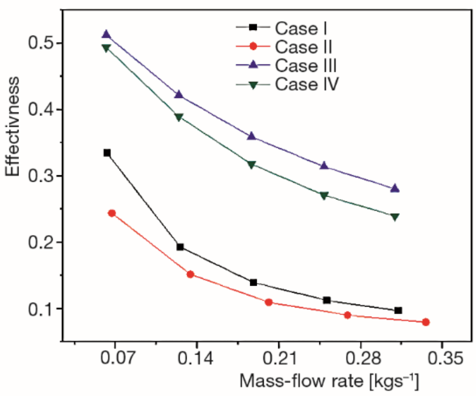
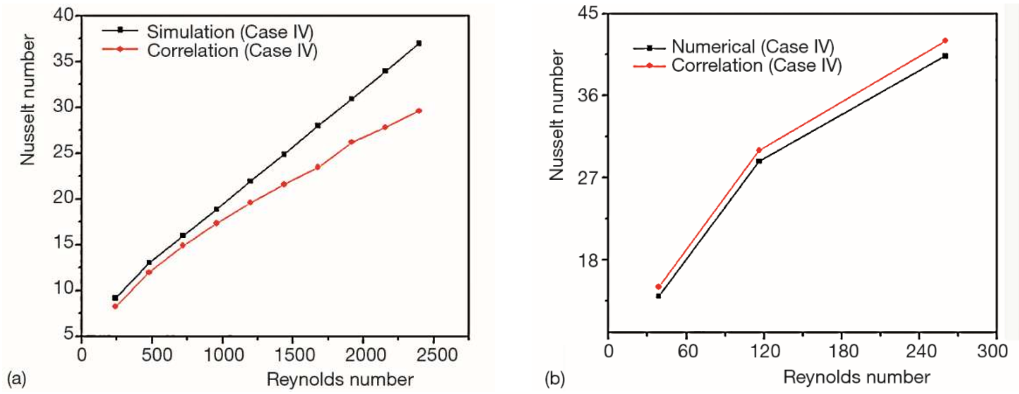


Figure 5. Mass-flow rate *vs.* effectiveness

The change in trend of effectiveness is dependent on mass-flow rate, which is in direct relation with heat capacity rate. Therefore, the effectiveness is decreased as mass-flow rate is increased. The change in temperature is decreased and heat capacity of the fluid is increased as shown in fig. 5. Therefore, the effectiveness is decreased by increasing the mass-flow rate. The fluid properties such as specific heat and viscosity also have effect on the mass-flow rate, which would further influence on the effectiveness of PHE. Finally, the effectiveness of Case III is 23% higher than that of Case I, while it is 9% for Cases II and IV. It can be concluded that the effectiveness of HE also depends on the type of working fluid but not only on design of plate. So, the selection of working fluid is also very important whether it is gas or liquid.

Numerical validation

The basic phenomenon of heat transfer devices is based on the convection heat transfer. Therefore, in order to verify the numerical simulation, it is necessary to analyze the convection heat transfer phenomenon and compare it with the correlation result. The variation in the Nusselt number with Reynolds number for corrugated and flat structures is shown in fig. 6. The turbulence inside fluid increased the heat transfer coefficient. Therefore, convective heat transfer with corrugated structure of PHE was higher than that of flat plate because corrugation pattern provided turbulence to fluid. The Nusselt number increased with Reynolds number and these curves trend showed similar behavior as *k-ε* realizable model in [27].



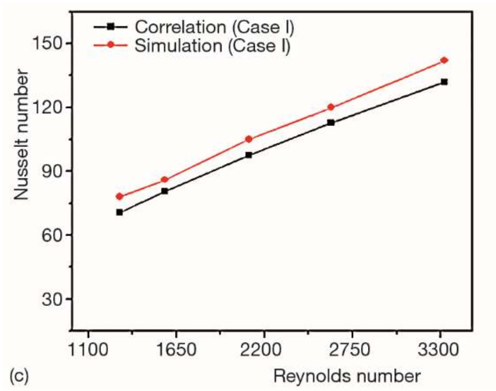


Figure 6. Reynolds number effect on Nusselt number; (a) Case IV, (b) laminar Case, and (c) Case I

Martin [44] developed the a correlation for the calculation of convective heat transfer with corrugated structure of PHE as given in eq. (10). The simulation results of the Case IV were compared with the correlation and the error between them was about 6% as shown in fig. 6(a). There was no prediction of correlation in the range of Reynolds number from 400 to 1000 [45]. There is no specific validity range for correlation, but it varies from 400 to 10000 of Reynolds number [44-46]. Similarly, within laminar region for Case IV the deviation between numerical and correlation values is about 5%, which is also in the safe range as in fig. 6(b).

$$\mathrm{Nu} = C\,\mathrm{Re}^{n}\,(C = 0.436 \text{ and } n = 0.5367) \tag{10}$$

The Nusselt number was also calculated for Case I with correlation $\mathrm{Nu} = C\,\mathrm{Re}^{m}\,\mathrm{Pr}^{1/3}$ [35]. The values of constants are $C = 0.3$, $\dot{m} = 0.668$. The Nusselt number for Case I was analyzed numerically and compared it with the correlation as shown in fig. 6(c). The uncertainty between correlation and simulation results is about 7%.

This difference is acceptable in the thermal hydraulics and provides the assurance for further calculation with the FLUENT and verified that methodology and steps taken for simulation are correct. Therefore, CFD is an effective tool to calculate and predict the thermal performance.

Effect of different structures on pressure drop

The change in pressure drop with the mass-flow rate is shown in fig. 7. Pressure drop was measured at different mass-flow rates for the PHE. Pressure drop is also dependent upon the density of liquid, therefore, pressure drop for water is higher than that of air.

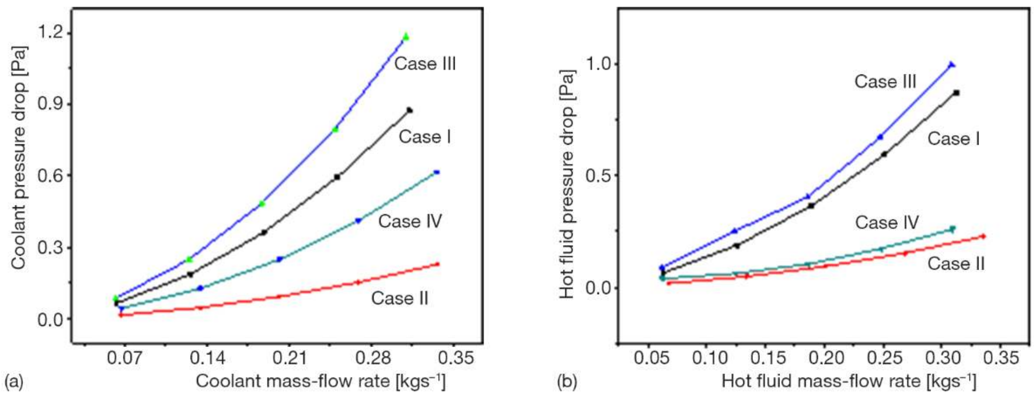


Figure 7. Effect of mass-flow rate on pressure drop Δ*p*; (a) coolant flow and (b) hot fluid

Pressure drop with the corrugated structure of the PHE is higher in comparison with flat plate, but this increase can be neglected as compared to increase in the heat transfer rate because corrugation pattern enhance the turbulence. The increase in pressure drop across the coolant side of corrugated PHE is 15% higher than that of flat PHE. Pressure drop is increased with Reynolds number due to variation in the velocity of working fluid and this increase is in accordance with [37, 38].

Pathlines

The pathlines in figs. 8(e) and 8(f) shows that direction of fluid is according to path from inlet towards outlet. The pathlines are the path which followed by particle from inlet to outlet. It can be seen from figs. 8(e) and 8(f) that pathlines for both flat and corrugated heat exchanger are from inlet to outlet.

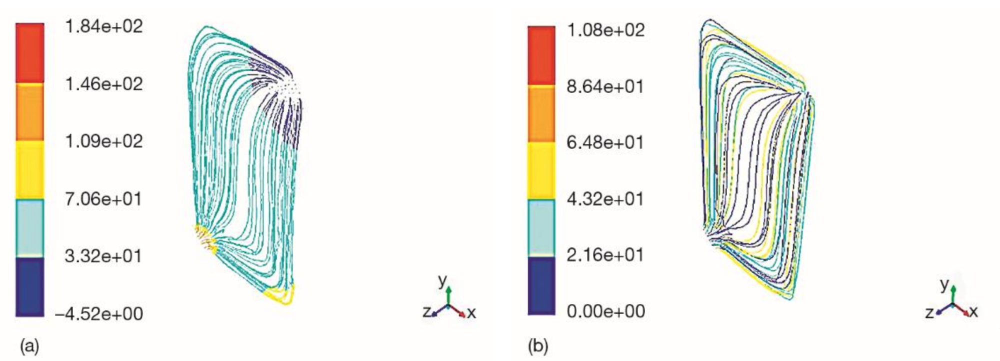


Figure 8. Pathlines for flat and corrugated structure of PHE; (a) pathlines for corrugated structure and (b) pathlines for flat structure (*for color image see journal web site*)

Conclusions

The PHE with the different structures were simulated using CFD with counter flow of the working fluids. The fluid-flow rate, pressure drop, outlet temperature, effectiveness, heat transfer rate, and Nusselt number for two fluids (*i.e.* water and air) have been analyzed. The result of this study is helpful for the design of highly efficient PHE and provided a way to improve the effectiveness of PHE. Main findings of the analyses are as follows.

- The heat transfer rate with corrugated structure of PHE is 20% higher than that of flat structure of PHE, which is 10% in case of air. Therefore, selection of working fluid and structure of HE is very important to enhance the effectiveness and heat transfer rate.
- The effectiveness of PHE depends on its design, mass-flow rate and type of fluid. The effectiveness of corrugated PHE is 23% higher than that of flat plate with water as working fluid and it's about 9% with air as working fluid.
- The numerical values for convective heat transfer of corrugated and flat PHE are in good agreement with correlation. The error between numerical and simulation results is ~5-7%.
- Pressure drop for the corrugated plate with water and air is high as compared to that of flat plate and this change can be ignored because increase in heat transfer rate and coefficient is higher as compared to this loss.
- According to heat transfer engineering point of view, this concept of corrugation and selection of the working fluid will be helpful for the design of modular HE for SMR and also for other high energy recovery devices.

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Nomenclature

A – area, [m^2]
C_p – specific heat, [KJkg^{-1}K^{-1}]
D_h – hydraulic diameter, [m]
V – volume flow rate, [m^{3}sec^{-1}]
h – heat transfer coefficient, [Wm^{-2}K^{-1}]
K – thermal conductivity, [Wm^{-2}K^{-1}]
k – turbulence kinetic energy
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
Nu – Nusselt number, (= hD_h/k)
p – pressure [Pa]
L – length, [m]
Pr – Prandlt number
Q – heat transfer rate, [W]
Re – Reynolds number, (= $VD_h/A\nu$)
ΔT – temperature difference, [ºC]

Greek symbols

ρ – density, [kgm^{-3}]
ν – kinematic viscosity, [m^{2}s^{-1}]
μ – dynamic viscosity N, [sm^{-2}]
ε – turbulence kinetic energy dissipation rate

Subscripts

w – wall

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