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Performance of a square, cross-corrugated, polymer film, compact, heat-exchanger with potential application in fuel cells

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Abstract

This paper describes an experimental investigation of the performance characteristics of a novel, cross-corrugated, polymer film, compact, heat-exchanger (PFCHE) made from poly ether ether ketone (PEEK). The aim is to develop *Jh* and *f* correlations over a range of Reynolds numbers under laminar conditions to be used in alternative heat-exchanger designs for potential applications in the fuel-cell industry. The incentive for adopting these designs is the huge weight, energy and cost savings involved. Design correlations for square units are key tools in obtaining alternative designs for applications that are presently monopolized by metallic heat-exchangers. The design correlations are establised and then used to perform case studies in selected applications in the fuel-cell industry to suit the fluids and the configuration.

Keywords: Polymer compact heat-exchanger; Process intensification; Poly ether ether ketone; Heat-transfer; Fuel cells

1. Introduction

The vast majority of presently available and commercially used heat-exchangers are made from metals such as stainless-steel. The use of metals provides certain significant disadvantages in terms of weight and cost. Since metals are good conductors of heat, the atmosphere surrounding the heat-exchanger provides either a receptor for unwanted heat to a coolant fluid or an unwanted extractor of heat from a heating fluid employed in the heat-exchanger. In addition, the processing of corrosive fluids is quite limited and generally demands the use of specialized, expensive metals. Also, most metals are easily wetted by liquids, which in turn promotes their interaction with the liquid via, for example, chemical reactions and fouling of the metal. Given these considerations, it is desirable to find an alternative material of construction for heat-exchanger apparatus that can address these shortcomings and also acquire high heat-exchange efficiencies and be easily fabricated. This is where the use of polymers comes into play. In accordance to this need and in order to enhance further the thermal performance of existing polymer compact heat-exchangers, thin polymer films have been adopted in a new design [1], as opposed to the more conventional shell and tube, plate or coil configurations. In current designs, the wall thickness can only be decreased to around 0.5–1 mm without affecting the mechanical strength of the polymers. The use of polymer films of approximately 100 μm thick is in fact possible and these will promote better thermal performance. In order to minimize the thermal resistance offered by polymeric materials, a polymer film, compact, heat-exchanger, with films of 100-μm thickness has been developed by Process Intensification & Innovation Centre (PIIC) at the University

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Nomenclature

AL	aluminium
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
d_h	hydraulic diameter (mm)
di	de-ionised water
f	friction factor
h	film heat-transfer coefficient (W m^{-2} K^{-1})
Jh	Colburn factor ($StPr^{2/3}$)
k	fluid thermal conductivity (W m^{-2} K^{-1})
L	fluid path length (m)
Nu	Nusselt number (hd_h/k)
Pr	Prandtl number ($cp\mu/k$)
Re	Reynolds number ($\rho vd_h/\mu$)
SS	stainless-steel
St	Stanton number ($Nu/RePr$)
T	temperature (K)
v	velocity (m s^{-1})
WEG	water–ethylene glycol mixture
Greek letters	
ΔP	pressure drop (kPa)
μ	viscosity of fluid (Ns m^{-2})
ρ	density of fluid (kg m^{-3})

of Newcastle upon Tyne, UK. Corrugations on the films also assist heat-transfer and encourages more mixing of the fluid flow.

In this paper, case studies are conducted on a square, cross-corrugated, polymer film, compact heat-exchanger (PFCHE). A case study is simply a feasibility study where an alternative heat-exchanger design is produced, to replace a conventional design for a suitable application. The motivation for adopting the alternative PFCHE design is increase in heat-transfer and energy efficiency, as well as weight and cost savings. Indeed performing a case study is the 'tried and tested' route undertaken to assess the feasibility of any novel intensified unit, in this case a PFCHE. The main element in performing the case studies is to incorporate the PFCHE heat-transfer and pressure-drop data, in the form of *Jh* and *f* correlations, towards the development of alternative designs. This is achieved by conforming to the conventional design specifications, e.g., the duty required and pressure drop limitations. The industrial companies involved in disclosing the specifications relevant for the case studies are Honeywell SERCK (UK) and Xcellsis (USA). The case studies are considered to be useful by industry in order to generate data for performance, cost, weight reduction and fuel or energy saving comparisons. A water/water system has been investigated. The correlations developed were then used in alternative designs of fuel-cell heat-exchangers. The driving force behind this approach is the considerable weight and energy benefits to be gained.

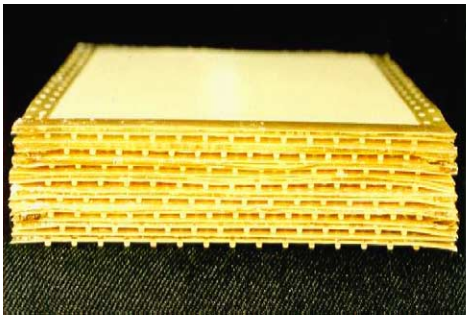

Fig. 1. Diagram of stacked PEEK films.

2. Experimental apparatus: design details and test procedure

Using 100-μm, corrugated, poly ether ether ketone (PEEK) films, which had a corrugation width of 2 mm and a corrugation height of 1 mm, a square module was fabricated. Details of the PEEK film and the cross-corrugated configuration have been explained previously [1]. The square PFCHE unit consisted of a number of corrugated PEEK sheets. The number of sheets used can vary for the different fluid systems and range of flow rates tested. The dimensions of the sheets were 13.5 cm × 13.5 cm. The film thickness of the corrugated sheet was approximately 70 μm (100 μm for non-corrugated). The sheets were stacked together, each rotated at 90° with respect to the next sheet, which created a cross-corrugated matrix. The stacked sheets are illustrated in Fig. 1.

The polymer sheets were arranged in this manner, to ensure that a perfect cross flow was obtained and that there was no mixing of the flows (hot and cold streams did not mix as they flowed through the heat-exchanger). This was achieved by carefully sealing the edges of the sheets, such that successive sheets formed a cross corrugation. This means that the corrugations cut one another at right angles as they ran along the length of the heat-exchanger, compressing several of the above sheets and sealing them to prevent any leakage. Sealing the edge of the sheets created the flow passage for each stream. This was done using a sealant (Araldite AV 119). An illustration of the sealed PEEK films is depicted in Fig. 2.

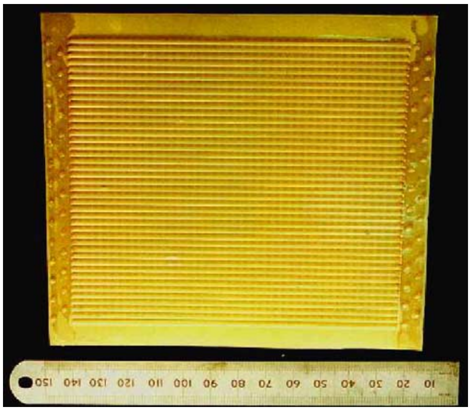

Fig. 2. Diagram of sealed PEEK films.

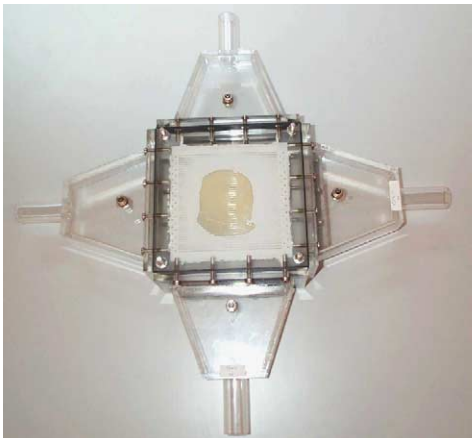

Fig. 3. Diagram of square PFCHE.

PEEK films are used because they can be easily corrugated and have excellent chemical, mechanical and thermal stability. They have a continuous service temperature of about 220 °C, and can withstand a differential pressure of about 1000 kPa. The stacked and compressed films were then placed inside a perspex housing. By doing this, four isolated compartments were formed, namely, one each for the inlet and the outlet of the hot and cold streams, respectively. The heat loss through the walls of the perspex housing was negligible. A diagram of the square PFCHE is shown in Fig. 3 and a schematic version is illustrated in Fig. 4.

2.1. System: water/water

For the water/water system [2] and [4], 44 corrugated PEEK sheets were employed. The water flow rates were measured using '35S' type rotameters. The hot water supply was taken from a reservoir that included both a heater and a temperature controller. Hot water from the reservoir was supplied to the heat-exchanger by a pump that could develop a 9 m head. Tap water was used to supply the cold water stream. The inlet and outlet temperatures were monitored using thermocouples that were placed mid-way down the exchanger stack, in the inlet and outlet chambers. K-type thermocouples were used and were dropped from the top of the chamber, and held in position by a thin glass tube. Temperatures were recorded by a digital recorder, which had an accuracy of ±0.1 °C. To measure the pressure drop across the heat-exchanger, tappings in the form of glass tubes were taken from the inlet and outlet chambers. These were connected to a digital manometer by means of flexible tubes. The digital manometer had an accuracy of ±0.01 kPa. A simplified flow diagram for the water/water experiments is shown in Fig. 5.

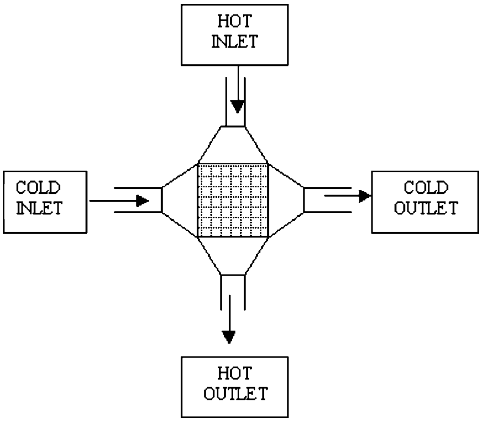

Fig. 4. Schematic of square PFCHE.

3. Experimental results

3.1. Colburn factor (Jh)

The Colburn factor, *Jh*, decreases as the *Re* increases. This trend is expected as it obeys the Colburn factor definition [3], where *Jh* is inversely proportional to *Re*, see Fig. 6 i.e.

$$Jh = St\, Pr^{2/3} = \frac{hd_{\mathrm{h}}\, Pr^{-0.33}}{k\, Re} \quad (1)$$

Nevertheless, slight scatter of data does occur from this proportional trend. This may be due to the higher relative uncertainty at low water-flow rates. To overcome this, experimental readings (temperatures and pressure drops) were repeated for the low water flow-rates to decrease the errors generated and consequently to optimize the accuracy of the *Jh* correlation. This correlation was developed by fitting the best curve through the data points; executed using Microsoft Excel. The correlation is as follows:

$$Jh = 1.3886 Re^{-0.6337}, \quad \text{for } 87 < Re < 235 \quad (2)$$

3.2. Friction factor (f)

From the pressure drops measured for the range of water flow rates tested, the friction factors were calculated and plotted as a function of *Re*, as presented in Fig. 7. The friction factor decreases as *Re* increases, thus abiding to the definition [3].

$$f = \frac{2\Delta P d_{\mathrm{h}}}{4\rho v^2 L} \quad (3)$$

From this equation, it can be seen that the friction factor is inversely proportional to the square of the fluid velocity (v). Therefore, since $Re = \rho v d_{\mathrm{h}}/\mu$, it is shown through this equation that the friction factor is inversely proportional to the *Re* number. The best fitting curve for the friction factor data points was generated using Microsoft Excel. The friction factor correlation is as follows:

$$f = 32.797 Re^{-0.7192}, \quad \text{for } 87 < Re < 235 \quad (4)$$

The data in Fig. 7 indicate that there is negligible deviation or scatter, which leads to a tight distribution band. This suggests that the experimental pressure drops recorded are

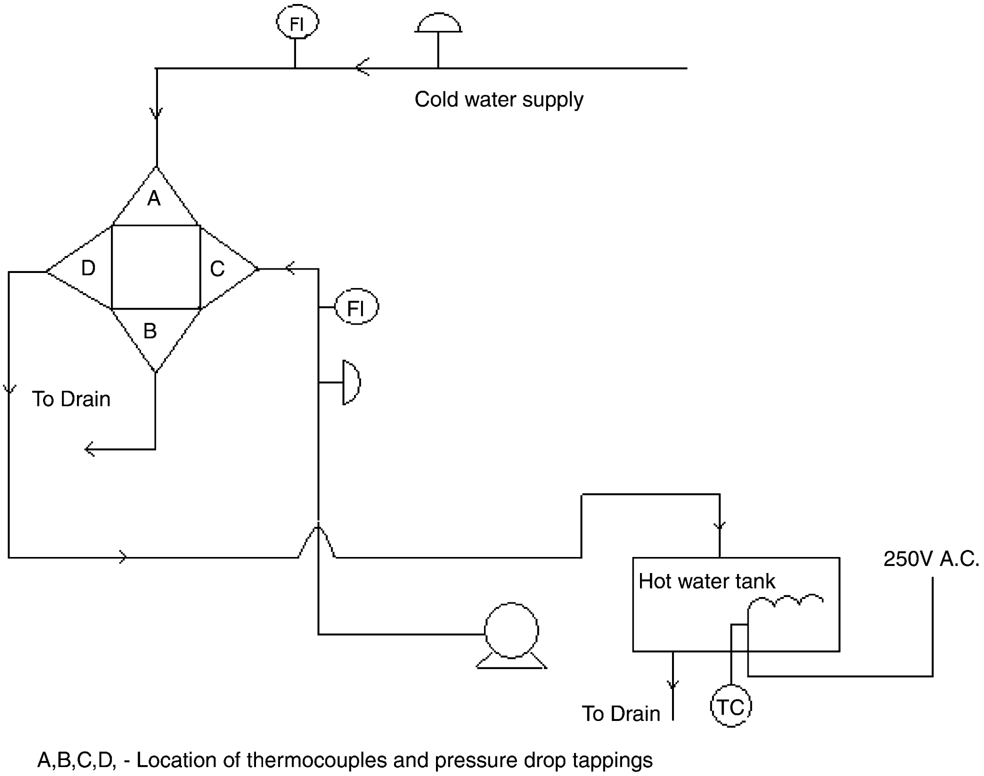

Fig. 5. Simplified flow diagram of square PFCHE experimental set-up for water/water system.

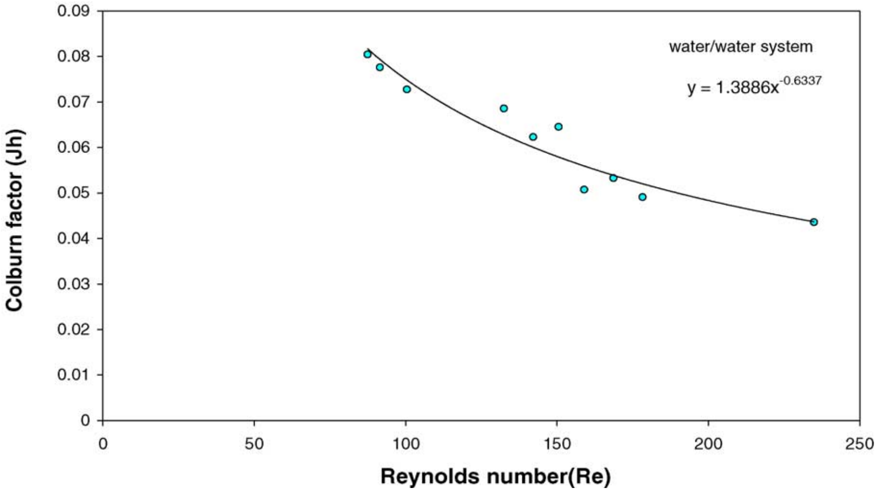

Fig. 6. Graph of Colburn factor (*Jh*) vs. Reynolds number (*Re*) for a square PFCHE in a water/water system.

accurate and can be used for the calculation of friction factors. The pressure drops vary between 0.1 and 1.2 kPa over the range of water-flow rates tested.

4. Square PFCHE for fuel-cell applications

In this section, three case studies for fuel-cell vehicle are considered. An alternative PFCHE design for a filter cooler and then for two fuel-cell heat-exchangers are evaluated. First, a brief background of the units is given in order to understand the reasons for employing them as case studies.

4.1. Potential for PFCHE as FCV heat-exchangers

The inherent benefits of the PFCHE have attracted potential applications in the fuel-cell industry for transport vehicles. These heat-exchangers are one of several other components that form the engine of a vehicle. By adopting the exchangers instead of conventional metal units, significant weight and cost savings can be achieved. Nevertheless, both

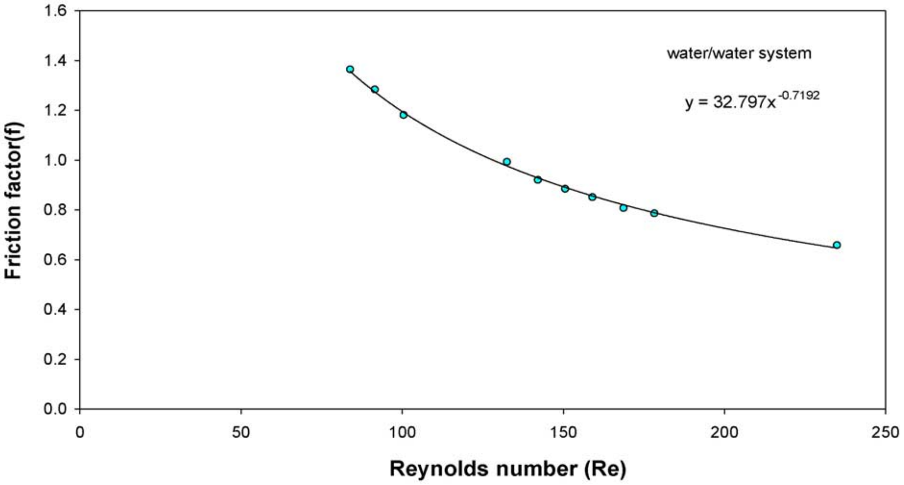

Fig. 7. Graph of friction factor (*f*) vs. Reynolds number (*Re*) for a square PFCHE in a water/water system.

of these units are metallic and impose a limit to the options and advancement in design improvement for the transport industry. This limitation in the freedom of design can be addressed by using polymer film, compact, heat-exchangers. To widen the scope of improvisation for heat-exchangers in transport vehicles, case studies on the polymer film, compact, heat-exchanger (PFCHE) have been conducted. Using polymer as the alternative material of construction along with a novel configuration, the PFCHE is believed to bring several benefits over the metallic fuel-cell designs in terms of overall performance and energy savings. In this section, three fuel-cell units are discussed as case studies for the PFCHE. The heat-transfer fluids involved in these exchangers are deionised water and water–ethylene glycol mixtures (WEG). These fluids have similar physical properties to water. Bearing this in mind, the design correlations for the water/water system in a square PFCHE are adopted to develop the alternative designs. Nevertheless, to increase the accuracy of the case studies performed, the physical properties used for the alternative designs are based on water and water-ethylene glycol mixtures, tabulated in Microsoft Excel. The design correlations for the PFCHE water/water system need to be extrapolated, as the Re required in the metallic design exceeds the PFCHE correlation range. The design correlations used are as follows:

$$Jh = 1.3886 Re^{-0.3174}, \quad \text{for } 87 < Re < 235 \qquad (5)$$

$$f = 32.797 Re^{-0.7192}, \quad \text{for } 87 < Re < 235 \qquad (6)$$

4.2. Fuel-cell case studies

Three case studies were carried out in collaboration with Honeywell SERCK (UK) and Xcellsis (USA). Using the

Table 1
Specification for a filter cooler with duty 14.5 kW; design 1

Hot circuit		Cold circuit	
Fluid	Deionized water/pure glycol	Fluid	WEG
Required outlet temperature (K)	335	Inlet temperature (K)	330
Pressure (kPag)	310	Pressure (kPag)	310
Pressure drop (kPa)	<30	Pressure drop (kPa)	<30
Flow (lpm)	30	Flow (lpm)	30

1. Materials in contact with deionized water limited to 316 L or 347 stainless-steel, or low copper aluminium (if uncertain contact (Xcellsis); 2. Both water/ethylene glycol mixtures are at 50/50. Name, DI-Glycol filter cooler; duty, 14.5 kW; duty cycle, 100%.

Table 2
Specification for a fuel-cell heat-exchanger with duty 340 kW; design 2

Hot circuit		Cold circuit	
Fluid-clean side	Deionized water/pure glycol	Fluid-dirty side	WEG
Required outlet temperature (K)	343	Inlet temperature (K)	338
Pressure (kPag)	250	Pressure (kPag)	275
Pressure drop (kPa)	<30	Pressure drop (kPa)	<30
Flow (lpm)	600	Flow (lpm)	560

Design unit, Fuel-cell heat-exchanger-option A; duty, 340 kW; duty cycle, 100%.

Table 3
Specification for a fuel-cell heat-exchanger with duty 260 kW; design 3

Hot circuit		Cold circuit	
Fluid-clean side	Deionized water/pure glycol	Fluid-dirty side	WEG
Required outlet temperature (K)	343	Inlet temperature (K)	338
Pressure (kPag)	250	Pressure (kPag)	275
Pressure drop (kPa)	<30	Pressure drop (kPa)	<30
Flow (lpm)	500	Flow (lpm)	425

Design unit, Fuel-cell heat-exchanger-option B; duty, 260 kW; duty cycle, 100%.

Table 4
Alternative design and savings for a filter cooler with duty 14.5 kW; design 1

Materials	Stainless-steel (SS)	Aluminium (AL)	Polymer (PFCHE)	Weight savings (%)	
				SS	AL
Length (mm)	110	110	120	n/a	n/a
Width (mm)	110	110	120	n/a	n/a
Height (mm)	92	73	80	n/a	n/a
Weight (kg)	2.96	0.77	0.12	96	84
ΔP_{di} (kPa)	23.5	8.3	1.88	92	77
ΔP_{WEG} (kPa)	23.8	8.4	5.03	79	40

Design unit, DI-Glycol filter cooler; duty, 14.5 kW.

Table 5
Alternative design and savings for a fuel-cell heat-exchanger with duty 340 kW; design 2

Materials	Stainless-steel (SS)	Aluminium (AL)	Polymer (PFCHE)	Weight savings (%)	
				SS	AL
Length (mm)	300	300	300	n/a	n/a
Width (mm)	300	300	300	n/a	n/a
Height (mm)	320	240	180	n/a	n/a
Weight (kg)	65.3	18.8	2.33	96	88
ΔP_{di} (kPa)	50.0	26.3	20.80	58	21
ΔP_{WEG} (kPa)	44.6	23.5	13.90	69	41

Design unit, fuel-cell heat-exchanger; duty, 340 kW.

Table 6
Alternative design and savings for a fuel-cell heat-exchanger with duty 260 kW; design 3

Materials	Stainless-steel (SS)	Aluminium (AL)	Polymer (PFCHE)	Weight savings (%)	
				SS	AL
Length (mm)	300	300	300	n/a	n/a
Width (mm)	300	300	300	n/a	n/a
Height (mm)	285	229	322	n/a	n/a
Weight (kg)	58.4	17.9	4.26	93	76
ΔP_{di} (kPa)	44.1	20.8	7.05	84	66
ΔP_{WEG} (kPa)	33.3	15.7	5.06	85	68

Design unit, fuel-cell heat-exchanger; duty, 260 kW.

Table 7
Summary of weight savings for the PFCHE case studies

Alternative PFCHE design	Duty (kW)	Weight savings (%)	Pressure drop savings (%)
Filter cooler	14.5	96 (SS), 84 (AL)	86 (SS), 59 (AL)
Fuel-cell heat-exchanger	340	96 (SS), 88 (AL)	64 (SS), 31 (AL)
Fuel-cell heat-exchanger	260	93 (SS), 76 (AL)	83 (SS), 67 (AL)

design correlations for a water/water system, prototypes were designed for deionised-water/glycol systems and compared with aluminium and stainless-steel units. The designs, which are used in fuel-cell-driven vehicles, are as follows:

1. Filter cooler with duty 14.5 kW.
2. Fuel-cell heat-exchanger with duty 340 kW.
3. Fuel-cell heat-exchanger with duty 260 kW.

The specifications for the three heat-exchangers, provided by Honeywell SERCK's client Xcellsis are presented in Tables 1–3, respectively.

Based on the data provided in Tables 1–3 alternative designs for PFCHEs were carried out in order to meet the heat-transfer requirement. The results of the case studies are shown in Tables 4–6. The terms (AL) and (SS), refer to aluminium and stainless-steel units, respectively.

It can be concluded that by using the PFCHE as an alternative for fuel-cell heat-exchangers, significant weight as well as pressure drop savings can be achieved. In all the case studies performed, the PFCHE design weighs less than a quarter of the fuel-cell units. In addition, the average pressure drops of the alternative PFCHE designs are much lower, compared with both the stainless-steel and aluminium units. These positive results will consequently translate into considerable fuel and, therefore, energy savings.

5. Conclusions

From the case studies conducted, it can be seen that there is a huge incentive for using the square PFCHE as an alternative to conventional metallic units, due to the tremendous energy and cost savings generated. In addition to this, the PFCHE designs are also more compact, require less space, are lightweight, and easy to maintain.

A summary of the weight savings achieved, when adopting the PFCHE design for the four case studies conducted in this study is given in Table 7. It can be seen that, in general, the PFCHE designs weigh less than a quarter of the conventional metallic units whilst the pressure drop savings exceed 75% and 40% for the stainless-steel and aluminium units, respectively. This is indeed a huge incentive to adopt the PFCHE as an alternative to conventional metal designs.

Acknowledgements

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