



# Development of novel plate heat exchanger using natural graphite sheet

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## ABSTRACT

Natural flake graphite sheets have superior physical properties such as: high in-plate thermal conductivity ( $300\text{--}600\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ), light weight ( $2.1\text{ g}\cdot\text{cm}^{-3}$ ), negligible coefficient of thermal expansion and resistivity to corrosion under high temperatures. With the new roll-embossing process, fabrication of graphite sheets with different patterns has become fast and economical. These properties make natural graphite an excellent candidate for thermal applications, such as heat exchangers (HEXs), as an alternative to metallic alloys. This study presents a new fabrication method for chevron-type plate HEXs, as a proof-of-concept demonstration, using flat embossing process. To measure the performance of the proposed graphite plate heat exchanger, a custom-designed water-water experimental testbed is designed based on ANSI/AHRI Standard 400. The heat transfer rate and the pressure drop of the fabricated graphite plate heat exchanger are compared to a conventional stainless-steel chevron HEX with similar plate dimensions and number of plates. Compared with the commercially available unit, the proposed graphite plate heat exchanger shows identical thermal performance and a 26% higher pressure drop, due to its narrower channel design. This provides a promising platform for future optimized designs of efficient, corrosion-resistance, and cost-effective graphite-based heat exchangers for a number of industrial applications.

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## 1. Introduction

Heat exchangers have been extensively used in applications such as oil and gas industry, food and chemical processing, power generation, refrigeration, and air conditioning systems. Fast industrialization and rise in energy needs, developments in chemical, petrochemical and HVAC systems have led to an ever-increasing need in the market for efficient and compact heat exchangers. The heat exchanger market value is estimated to grow from USD 13.89 Billion in 2017 to USD 20.65 Billion by 2022 [1]. In any heat exchanger, other than design considerations, material selection plays a crucial role in determining its maintenance cost and life span. For example, heat exchangers made from a material with high coefficient of thermal expansion, are more likely to damage from thermal stresses under swinging operating temperatures. Conventional heat exchangers are mostly made from metallic alloys, such as aluminum, copper, and steel. These alloys have good heat transfer properties, such as high thermal conductivity, and are easy to manufacture and cost-effective. However, aluminum, copper and steel are prone to corrosion when subjected to corrosive environments. Heat exchangers in urban air conditioning systems,

automotive, heat recovery from flue gas, and chemical and petroleum processing can be subjected to such damages [2,3].

Natural graphite is a corrosion-resistant material and has an exceptionally high thermal conductivity ( $300\text{--}600\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  in the in-plane direction vs aluminum  $200\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ), low density ( $2.1\text{ g}\cdot\text{cm}^{-3}$  vs. aluminum  $2.7\text{ g}\cdot\text{cm}^{-3}$ ), negligible coefficient of thermal expansion and low material cost. These properties make natural graphite an excellent material for heat exchanger applications [4–6]. Artificial synthetic resin impregnated graphite is now being used by several manufacturers such as SGL Carbon and Group Carbone Lorraine to produce graphite heat exchangers under DIABON® and GRAPHILOR® brands, respectively. In the manufacturing process of artificial graphite blocks, temperatures as high as  $3000\text{ °C}$  is required to induce crystalline structures. These blocks are then machined to a desired shape to be used in heat exchanger industry. Although being corrosion resistant, the high manufacturing and machining costs of thermal products made from artificial graphite has been a significant obstacle preventing their widespread adoption.

Among different types of heat exchangers, plate heat exchangers are considered compact as they provide a high heat transfer surface area per volume. In plate heat exchangers, the thin plate that transfers heat between the hot and cold streams is usually patterned. These thin plates can be fabricated from natural

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### Nomenclature

$L_w$	plate width (m)	$T_{c,o}$	cold fluid outlet temperature (K)
$L_p$	plate length (m)	$\dot{q}_h$	heat transfer rate from hot loop of the heat exchanger (W)
$l$	corrugation pitch (m)	$\dot{q}_c$	heat transfer rate from cold loop of the heat exchanger (W)
$b$	corrugation depth (m)	$\dot{q}_{ave}$	average heat transfer rate of hot and cold loop (W)
$\emptyset$	plate shift angle	$d_h$	hydraulic diameter (m)
$\beta$	chevron angel	$\dot{m}_h$	mass flow rate of hot loop of the heat exchanger ( $\text{kg}\cdot\text{s}^{-1}$ )
$d_{port}$	port diameter (m)	$\dot{m}_c$	mass flow rate of the cold loop of the heat exchanger ( $\text{kg}\cdot\text{s}^{-1}$ )
$Re_{d_h}$	Reynolds number in plate heat exchanger channel	$c_p$	specific heat capacity ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{C}^{\circ-1}$ )
$T_{h,i}$	hot water inlet temperature (K)		
$T_{h,o}$	hot water outlet temperature (K)		
$T_{c,i}$	cold water inlet temperature (K)		

graphite sheets and patterned via embossing process without any machining. More than 60 different surface patterns have been developed throughout the last century. Among these, chevron patterns are the most commonly used by the manufacturers. They increase the heat transfer surface area, promote swirl flow, and disrupt the formation of boundary layers [7]. There are several geometrical design parameters for a chevron plate heat exchanger that is shown in Fig. 1. Plate width, length, chevron angle, corrugation depth, and pitch are the design parameters of a plate heat exchanger.

Researchers have analyzed the effect of each design parameters (Fig. 1) on heat transfer and pressure drop individually. A summary of the available literature and the reported performance is listed in Table 1.

Durmus et al. [8] investigated the effect of different surface profiles on heat transfer and pressure drop of plate heat exchangers

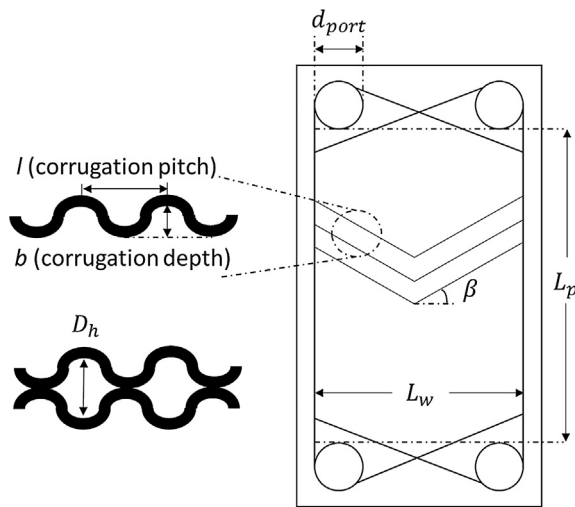


Fig. 1. Design parameters of a chevron plate heat exchanger.

experimentally, comparing flat, asterisk, and corrugated plates. They showed that the corrugated surface profile has a higher heat transfer rate due to induced turbulence as well as a higher pressure drop [8]. Dovic et al. [9] conducted experiments in two chevron angles of  $28^\circ$  and  $61^\circ$  and three aspect ratios (pressing depth/wave length) of 0.5, 0.4 and 0.27, respectively. They concluded that surfaces with deeper grooves (higher aspect ratio) have a lower surface goodness factor, which is a non-dimensional parameter that shows heat transfer benefit over pressure drop cost [9]. Yin et al. [10] investigated the influence of plate's shift angle (shown in Fig. 2) on heat transfer coefficient and friction factor of a plate heat exchanger. The shift angle defines the alignment of upper and lower corrugated plates relative to each other. They concluded that the highest heat transfer coefficient was obtained when  $\phi = 180^\circ$  due to higher swirl recirculation of the fluid in channels [10].

In this study, a new graphite plate heat exchanger is built from natural graphite sheet using flat embossing technology. The proposed plate heat exchanger can be mass-produced using a roll-embossing process that is a cost-effectiveness and can reduce the manufacturing costs of graphite heat exchangers. Using the available results in the literature, listed in Table 1, the proposed graphite plate heat exchanger is designed with a 0.25 aspect ratio and a  $180^\circ$  shift angle.

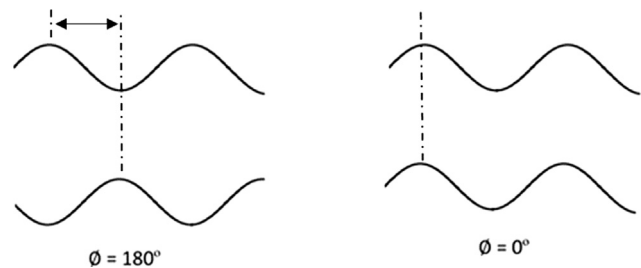


Fig. 2. Plate shift angle definition.

Table 1

Summary of the literature review on the design parameters of a plate heat exchanger.

Ref.	Heat transfer fluids (Hot/Cold)	Reynolds number range	Design parameter studied	Remarks
Durmuş et al. [8]	Water/Water	$50 < Re_d < 1,000$	Plate surface profile	Experimentally compared heat transfer, pressure drop, friction factor, and exergy loss between asterisk, flat, and corrugated plate design
Dovic et al. [9]	Water-glycol/Water-glycol	$0.1 < Re_d < 250$	Corrugation aspect ratio, Chevron angle	Experimentally studied influence of aspect ratio and chevron angle on thermal-hydraulic performance of corrugated plates
Yin et al. [10]	Air/Air	$2,000 < Re_d < 10,000$	Plate phase shift	Numerically studied the effect of phase shift on flow and heat transfer in corrugated channels

## 2. Fabrication process

Flexible graphite sheet with an area density of  $120 \text{ mg}\cdot\text{cm}^{-2}$  was first compressed down to 2 mm thickness with a rolling machine to increase the density. The compression also enhances the mechanical properties of the sheets and prepare them for the cutting process. To cut the sheets in size and to form the circular holes, sheets were mounted on a cutting die and cut using a clicker press. To fabricate the chevron patterns on graphite sheets, a set of aluminum dies with chevron patterns were designed and fabricated. These dies were installed on a 200 kN mechanical press, the graphite plates were mounted in between the dies and compressed with the press. This flat embossing process on graphite was developed by Terrella Energy Systems Ltd. The fabrication process of the chevron graphite heat exchanger is shown in Fig. 3. Creating chevron patterns on graphite sheets with the proposed technique is faster and more cost efficient than conventional machining techniques of graphite blocks. Fig. 4 shows a closer view of the chevron patterns built using flat embossing process and a picture of the fully assembled graphite plate heat exchanger.

In order to further improve the mechanical properties of the graphite, they went through a resin impregnation process. In this process, sheets were put in the Herson® Porosity Sealant (HPS) 994 resin bath under vacuum pressure for two hours. There the air pores of graphite were filled with resin to increase the mechanical strength of the plates.

Conventional metallic plate heat exchangers use gaskets or brazing between the plates, to create path for hot and cold fluid, and to prevent the mixture of the fluids, and the leakage of the fluids from heat exchanger to the environment. In the present design, no gasket was used, instead male and female grooves were designed on the plates. An automatic glue dispenser machine, Herson 394®, was applied to the female grooves and the plates were stacked on top of each other, so that the male grooves were fit into the females. This method is rather easier than the brazing technique that is used for metallic plate heat exchangers. The heat exchanger was leak tested by applying air pressure at 70 psi on both sides at the same time. Table 2 shows the design parameters

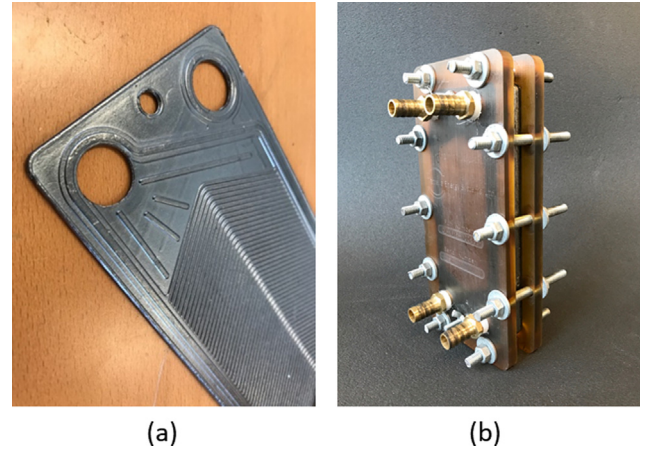


Fig. 4. (a) Chevron patterns on natural graphite sheet built using flat embossing process; (b) fully assembled graphite plate heat exchanger.

of the fabricated natural graphite-sheet plate heat exchanger in our lab:

## 3. Experimental setup

A custom-made experimental testbed was designed and built to measure the total heat transfer rate and pressure drop of the proposed graphite heat exchangers according to ANSI/AHRI Standard 400 [11]. As shown in Fig. 5, a heating and a cooling heat pump unit supplied the hot/cold water as the heat transfer fluids. These units kept a constant temperature for hot/cold inlets and pumped them inside the loops. For both loops, a control valve was provided to control the flow rate. A Coriolis flow meter was used for the flow rate measurement. For the temperature measurement, four thermocouples were put before/after the heat exchanger to measure the inlet/outlet temperatures. For the pressure drop measurement, two pressure transducers were used before and after each loop. A list of all the sensors with their accuracy is given in Table 3.

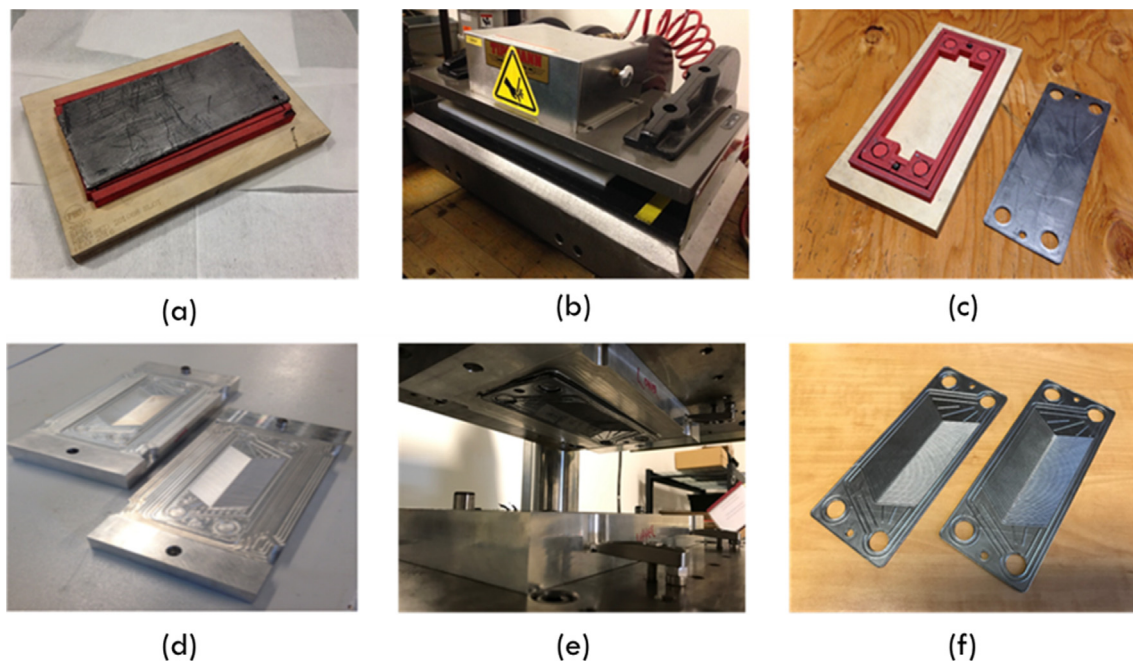


Fig. 3. Fabrication process of graphite plate heat exchanger: (a) Mounting graphite sheet on cutting die; (b) Cutting with hand-press machine to create circular holes; (c) Graphite plates after cut; (d) Preparing chevron dies; (e) Pressing graphite plates with chevron dies; (f) Chevron plates after resin treatment.

**Table 2**

Design parameters of the chevron-type graphite plate heat exchanger (GHEx), see Fig. 1 for parameters definition.

Design parameter	Value
Plate length ( $L_p$ )	151 mm
Plate width ( $L_w$ )	64 mm
Corrugation pitch ( $l$ )	2 mm
Corrugation length ( $b$ )	0.5 mm
Chevron angle ( $\beta$ )	30°
Port diameter ( $d_{port}$ )	19 mm

**Table 3**

Experimental setup sensors information.

Sensor	Supplier, Model	Accuracy	Measurement range
Thermocouple	Omega, T type	±0.5 °C	0–220 °C
Pressure transducer	Omega, PX305	0.25%	0–200 kPa
Flow meter	FLOMEC, OM015S001	0.5%	1–40 L·min <sup>-1</sup>

For a more accurate measurement of temperatures, thermocouple connections were thermally insulated. Surface of the heat exchanger was also carefully insulated to minimize the heat exchange to the ambient. Ideally in the experiments all the heat transfer between hot and cold fluids should happen inside the heat exchanger. The experimental setup configuration and insulated parts are shown in Fig. 6. An uncertainty analysis is presented in Appendix A.

The total heat transfer rate inside the heat exchanger was calculated by averaging the heat transfer rate from the hot side and cold side, as shown in the Eqs. (1)–(3) following Ref. [12].

$$\dot{q}_c = \dot{m}_c c_p (T_{c,out} - T_{c,in}) \quad (1)$$

$$\dot{q}_h = \dot{m}_h c_p (T_{h,in} - T_{h,out}) \quad (2)$$

$$\dot{q}_{ave} = \frac{\dot{q}_c + \dot{q}_h}{2} \quad (3)$$

where:

$T_{h,i}$  = Hot fluid inlet temperature (K)

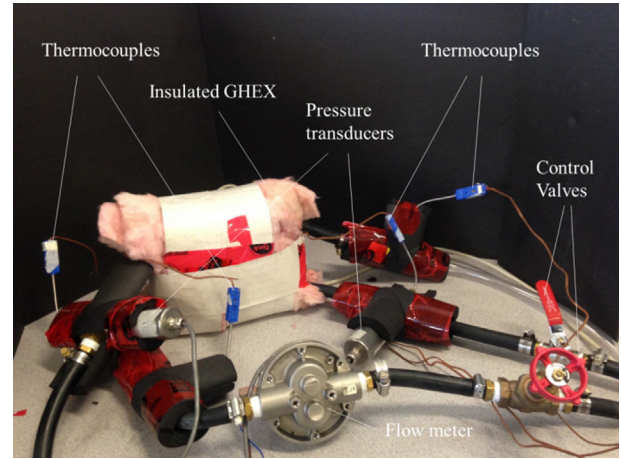
$T_{h,o}$  = Hot fluid outlet temperature (K)

$T_{c,i}$  = Cold fluid inlet temperature (K)

$T_{c,o}$  = Cold fluid outlet temperature (K)

#### 4. Results and discussion

The experimental setup was used to compare the thermal and hydraulic performance of the built graphite plate heat exchanger. In addition, we tested an off-the-shelf stainless-steel chevron plate HEX to benchmark the testbed and our experimental results. The off-the-shelf plate was purchased from Brazetek, (model BT3X8-10), and had almost the same size and the exact same number of plates as the built graphite plate heat exchanger in our lab. The



**Fig. 6.** Experimental setup configuration; plate graphite heat exchanger (GHEx) is insulated.

design parameters provided by the manufacturer are listed in the Table 4.

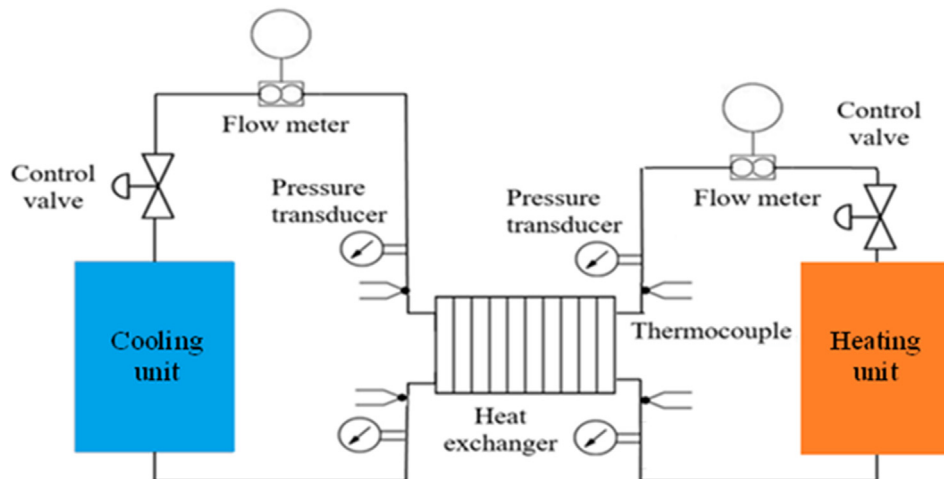
Two experiments were conducted with the same flow rates and inlet temperatures of water on these two heat exchangers. Table 5 shows the experiments input parameters.

There was a 1.5% uncertainty for the heat transfer rate that can be calculated from the Eq. (4).

$$\frac{\delta Q}{Q} = \left( \left( \frac{\delta \dot{m}}{\dot{m}} \right)^2 + \left( \frac{\delta \Delta T}{\Delta T} \right)^2 \right)^{1/2} \quad (4)$$

Figs. 7 and 8 show the comparison between heat transfer and pressure drop of the two heat exchangers, respectively.

Our results show that the total heat transfer rate of the graphite plate is almost identical to the commercially available stainless-



**Fig. 5.** Schematic of our custom-built experimental setup.

**Table 4**

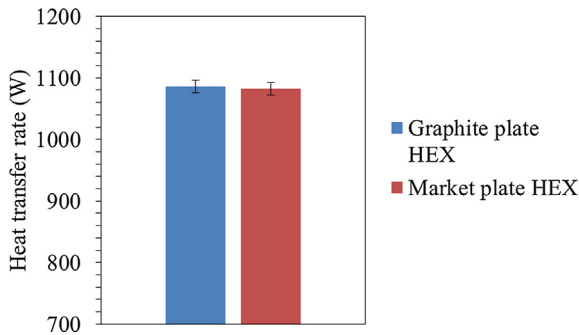
Design parameters of the off-the-shelf stainless-steel chevron plate heat exchanger, manufactured by Brazetek, (model BT3X8-10).

Design parameter	Value
Plate length ( $L_p$ )	153 mm
Plate width ( $L_w$ )	61 mm
Chevron angle ( $\beta$ )	30°
Port diameter ( $D_{port}$ )	19 mm

**Table 5**

Input parameters of the experiments.

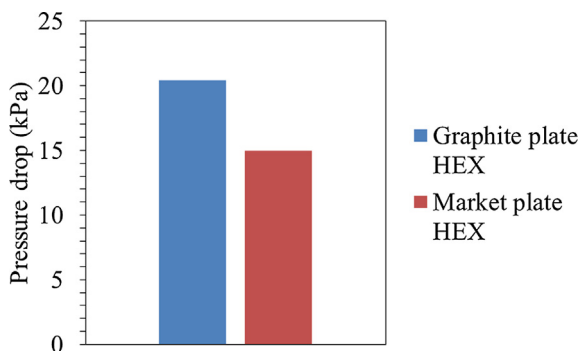
Experiment inputs	Properties
Working fluid of hot and cold loop	Water
Hot fluid inlet temperature	35 °C
Cold fluid inlet temperature	25 °C
Hot fluid inlet flow rate	6.0 L·min <sup>-1</sup>
Cold fluid inlet flow rate	2.2 L·min <sup>-1</sup>



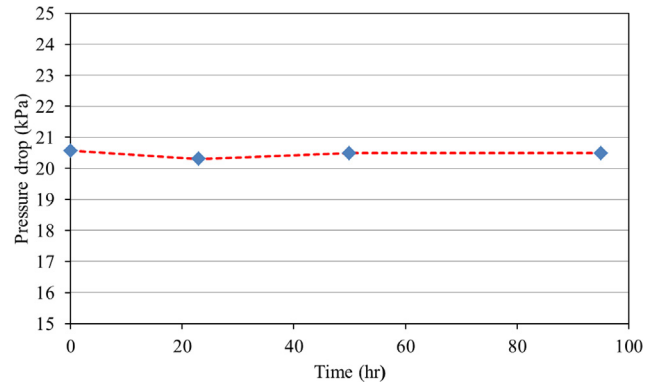
**Fig. 7.** Heat transfer rate comparison between the proposed graphite plate heat exchanger and the commercially available stainless-steel unit manufactured by Brazetek, (model BT3X8-10).

steel plate heat exchanger. The graphite heat exchanger however has a 26.0% higher pressure drop, which is due to its narrower channels. The plates of the graphite unit are stacked with a thin layer of glue in between, and the distance between the plates was limited to 0.5 mm by the thickness of the glue layer. In the stainless-steel heat exchanger this distance is 1.8 mm. The higher pressure drop can be remedied by an improved design of the chevron plates, which can be implemented in the next prototype.

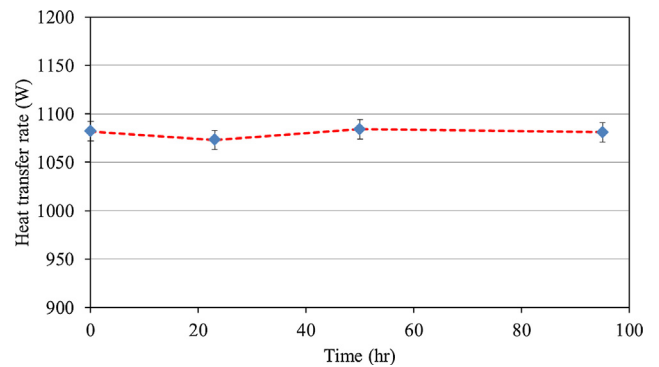
To check for the consistency of the graphite plate heat exchanger results, the performance was monitored for 100 h of steady-state operation as shown in Figs. 9 and 10. The variations for pressure drop data were as low as 0.27 kPa (1.3% of original value) and



**Fig. 8.** Pressure drop comparison between the proposed graphite plate heat exchanger and the commercially available stainless-steel unit manufactured by Brazetek, (model BT3X8-10).



**Fig. 9.** Pressure drop variation of graphite heat exchanger over time under steady-state conditions.



**Fig. 10.** Heat transfer rate variation of graphite heat exchanger over time under steady-state conditions.

9 W (0.8% of original value) for heat transfer rate data. The figures confirm that the performance is reasonably steady over time and no degradation was observed within the 100 h test.

### 5. Conclusions

Challenges with conventional metallic heat exchangers, such as corrosion and thermal shocks have been a limitation in application of heat exchangers. Alternative materials, such as titanium and artificial synthetic graphite are much more expensive than conventional metallic alloys and in some instances are less efficient due to their low thermal conductivities. Being Corrosion resistant, low material cost, and low manufacturing cost of the proposed embossing process, makes natural graphite sheets a potential replacement for these heat exchangers. In this study, a new graphite chevron-type plate heat exchanger was designed, and the fabrication steps were presented. The performance of the graphite heat exchanger was compared to a conventional stainless-steel plate heat exchanger, with the same number of plates and plate dimensions, using a custom-made water-water experimental test setup. The results showed that the performance of the proposed graphite plate heat exchanger, in terms of total heat transfer rate was almost identical with the stainless-steel unit and its pressure drop was 26.0% higher due to narrower channels. This study provided a promising platform for future optimized designs of efficient, corrosion-resistance, and cost-effective graphite-based heat exchangers for a number of industrial applications.

### Conflict of interest

The authors declared that there is no conflict of interest.

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## References

- [1] <<http://www.marketsandmarkets.com/PressReleases/heat-exchanger.asp>>, June 2018.
- [2] S. Kakac, H. Liu, A. Pramuanjaroenkij, *Heat Exchangers: Selection, Rating, and Thermal Design*, CRC Press, 2012.
- [3] B. Kužnicka, Erosion–corrosion of heat exchanger tubes, *Eng. Fail. Anal.* 16 (7) (2009) 2382–2387.
- [4] Al. Savvatimskiy, Measurements of the melting point of graphite and the properties of liquid carbon (a review for 1963–2003), *Carbon* 43 (6) (2005) 1115–1142.
- [5] Y. Gogotsi, Controlling graphene properties through chemistry, *J. Phys. Chem. Lett.* 2 (2011) 2509–2510.
- [6] F. Bagheri, M. Fakoor-Pakdaman, M. Bahrami, Utilization of orthotropic graphite plates in plate heat exchangers, analytical modeling, *Int. J. Heat Mass Transf.* 31 (77) (2014 Oct) 301–310.
- [7] R.K. Shah, W.W. Focke, Plate heat exchangers and their design theory, *Heat Transf. Equip. Des.* 227 (1988) 254.
- [8] A. Durmuş, H. Benli, İ. Kurtbaş, H. Gül, Investigation of heat transfer and pressure drop in plate heat exchangers having different surface profiles, *Int. J. Heat Mass Transf.* 52 (5) (2009) 1451–1457.
- [9] D. Dović, S. Švaić, Influence of chevron plates geometry on performances of plate heat exchangers, *Tehnicki vjesnik/Technical Gazette* 14, 2007.
- [10] J. Yin, G. Yang, Y. Li, The effect of wavy plate phase shift on flow and heat transfer characteristics in corrugated channel, *Energy Proc.* 14 (2012) 1566–1573.
- [11] ANSI/AHRI Standard 400, Standard for Performance Rating of Liquid to Liquid Heat Exchangers, 2015.
- [12] T.L. Bergman, F.P. Incropera, D.P. DeWitt, A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, 2011.