**Assessing the Thermo-Hydraulic Efficiency of Lung-Inspired Compact Plate Heat Exchangers Made Using Additive Manufacturing Techniques with Steel Aluminum and Titanium Powders**

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**Abstract:** The selection of material for compact plate heat exchangers (CPHEs) is of increasing importance due to global economic and supply constraints. Additionally, the influence of material selection on the thermo-hydraulic characteristics of CPHEs is an area of ongoing research. This study aims to address these issues by analyzing the thermo-hydraulic performance of CPHEs made from steel, aluminum, and titanium materials with small, complex channels. Using an additive manufacturing method (specifically Direct Metal Laser Sintering), lung-inspired CPHEs of identical geometry and roughness were manufactured from steel, aluminum and titanium powders. The thermo-hydraulic characteristics of CPHEs as well as that of a traditional one with Chevron-type, were investigated using both experimental and numerical techniques under specific operating conditions to determine the optimum between maximum heat transfer and minimum pressure drop. The findings of this study reveal that as the temperature difference between the inlet on the hot and cold sides, as well as the flow rate, were increased, there was a corresponding increase in both amount of heat transferred and loss of pressure across all investigated CPHEs. Compared to the chevron type brazed plate heat exchanger, the CPHE made from aluminum showed a 75.2% and 11.2% increase in heat transfer and a 31.8% and 10.9% reduction in pressure drop at 3 and 6 L/min, respectively, for a temperature difference of 90-40 °C. This study suggests that the use of materials with different thermal conductivities in CPHEs may offer a promising solution to achieve elevated heat transfer rates while minimizing pressure drop.

**Keywords:** 3D printing technique; Nature-inspired design; Compact heat exchanger; Metal powders; Plate geometry; Thermo-hydraulic assessment.

**1. Introduction**

In 2021, the Total Available Market (TAM) for heat exchangers was valued at $15.94 billion [1]. Furthermore, within this market, the plate and frame subtype accounted for a TAM of $5.49 billion [2]. Despite the COVID-19 pandemic causing a decrease in crude oil prices and an increase in electricity production, the heat exchanger industry was relatively unaffected, with some challenges such as manufacturing delays and disruptions in the supply chain for product demand. In the next 8 years, the plate and frame heat exchanger market is projected to experience an annual growth rate of 5.4% from 2022 to 2030, attributed to factors such as the minimal risk of leakage, superior corrosion resistance, and growing utilization in various industries including oil and gas, automotive, pharmaceutical, and petrochemical [2].

The gasketed plate heat exchanger (PHE) segment holds the largest market share in the plate and frame heat exchanger industry, accounting for approximately 55% [2]. This is attributed to its low leakage risk, scalability, and ease of cleaning. However, gasketed PHEs also face challenges such as gasket-related issues (leakage, corrosion, and cost), small volume (size, microchannel), high temperature, and high pressure. In response to these challenges, recent advancements in manufacturing technology have led to increased focus on the design and production of one-piece compact PHEs (CPHEs). Today, additive manufacturing methods are being applied in the heat exchanger industry, where 3D CPHEs are created by layering material powders.

Compactness which is the maximum heat transfer surface area that is in contact with fluids per unit volume is a key factor in the production of PHEs that are constrained by weight and volume limitations. CPHEs have several advantages, including small size, high heat transfer efficiency, greater contamination resistance, high operating pressures, robust design, and low manufacturing costs [3]. The increasing importance of compactness in plate heat exchangers (PHEs) has been facilitated by the progression of additive manufacturing techniques. These techniques have enabled the production of compact PHEs that possess solid, durable, lightweight, and intricate internal and external geometries.

The utilization of additive manufacturing techniques has the potential to enable the fabrication of next-gen Compact Plate Heat Exchangers (CPHEs) featuring complex topologies, which exhibit improved heat transfer properties and decreased pressure drop characteristics. These methods also offer benefits such as rapid production, low energy and material usage, and cost-effectiveness. This is especially beneficial for the fabrication of CPHEs that involve difficult-to-machine materials and complex geometries. Recent studies have demonstrated the capabilities of three-dimensional printing for the production of sophisticated features on compact heat exchangers. For example, Farjam *et al.* [4] used cold spraying of aluminum-alumina powder mixtures to create arrays of pyramid shaped fins on aluminum surfaces. Thermo-hydraulic performance assessments showed that the presence of alumina in the fins outperformed conventional fins. Arie *et al.* [5] used a specific method of additive manufacturing called "layer-by-layer line laser-welded" to create a heat exchanger made of high-density polyethylene sheets. The heat exchanger was experimentally tested and found to have better heat transfer properties when compared to traditional plate fin surfaces, specifically it had a better heat transfer coefficient for the same pressure drop. Arie *et al.* [6] used Direct Metal Laser Sintering (DMLS) to manufacture a manifold-micro-channel heat exchanger to use in dry cooling in power plants. Tested materials were stainless steel and aluminum and titanium alloys. The lowest fin wall thickness was used as 0.15 mm for the air side and 0.32 mm for the water side. The titanium alloy manifold-microchannel heat exchanger outperformed conventional heat exchangers with various fin types (plain plate, louvered, and wavy fins). In their computational and experimental study, Rastan *et al.* [7] investigated the effect of a longitudinal vortex generator in aluminum alloy mini-channel heat exchangers manufactured with DMLS techniques. The study reveals that vortex generators could increase convective heat transfer up to 300%. Ahmadi *et al.* [8] fabricated a sealed, ceramic, lung-shaped 3D-printed heat exchanger. The complexity of exchanger topology provided superior heat transfer especially for high-temperature energy efficient systems. Experimental comparison with ceramic, millichannel, 3D-printed heat exchangers showed that lung-shaped model performs better thermo-hydraulic characteristics. These studies demonstrate that additive manufacturing methods are well-suited to manufacture air-to-air or air-to-water heat exchangers with complex geometric structures in small sizes. The fact that the specific heat capacity and the density of gases like air are quite low compared to water. Hence greater surface area is required for same level of heat transfer. The fin structures are used to improve heat transfer but this results formation of mini- and micro-channels and complex geometries eventually.

There is limited literature on the thermo-hydraulic performance, small volume, durability, and reliability of CPHEs that utilize complex heat transfer topologies. Lowrey *et al.* [9] created two air-to-air CPHE prototypes made of aluminum and thermoplastic. The prototypes were identical. two identical prototype air-to-air CPHEs, one made of aluminum and the other made of thermoplastic (fused filament fabrication 3D printer). The study found that the thermal efficiency of both CPHEs was greater than 0.50 and demonstrated similar thermal properties. The aluminum CPHE exhibited 22% better thermal performance than the polymer CPHE. Göltaş *et al.* [10] fabricated a CPHE design with a plate surface lung pattern using DMLS as an additive manufacturing method to reduce pressure losses and increase amount of heat transferred. The CPHE was made of AISI 316 stainless steel powder, measuring 74 mm x 192 mm in size. The water-to-water CPHE was compared to a commercially used chevron-type brazed PHE of similar characteristics. The CPHE demonstrated 23% more effectiveness compared to the chevron-type brazed PHE at a flow rate of 6 L/min and under the same conditions. Ning *et al.* [11] produced three types of water-to-water CPHEs with stainless steel (316L) fins using laser powder bed fusion technology. The fin types were twisted, improved rectangular, and conventional. They conducted experimental tests and numerical simulations to assess the thermo-hydraulic characteristics of the CPHEs. The study found that the twisted-fin CPHE exhibited best thermal performance among investigated CPHEs. These studies suggest that the thermo-hydraulic performance of a CPHE produced by additive manufacturing is strongly dependent on both the material and the architecture. In their study, Ahmadi and Bigham (12) evaluated the thermal efficiency of a three-dimensional printed polymer composite plate heat exchanger (CPHE) with intricate internal configurations, specifically a lung-inspired design, at varying thermal conductivity levels, utilizing both experimental and numerical methods. They reported that the thermal performance of an air-to-water polymer CPHE is strongly dependent on both thermal conductivity and the optimal design with minimal thermal resistance. The lung-inspired polymer CPHE with high thermal conductivity offered an exceptionally high efficiency of 70-80% compared to metal-based heat exchangers. These cited studies have focused on evaluating the heat transfer performance of CPHEs that are manufactured using different geometries. However, it should be noted that there is no indication that the CPHEs being compared to each other have the same geometry and roughness. This means that the results of these studies may not be directly comparable, as the geometries and roughness of the CPHEs could have a significant impact on their thermal performance. A comprehensive examination is necessary to determine the impact of these factors on the overall performance of CPHEs.

Upon detailed review of the literature, it becomes apparent that the impact of the material used in CPHEs produced by additive manufacturing methods on their thermo-hydraulic performance has not been thoroughly investigated. This paper intends to fill this gap by introducing and investigating a lung-inspired CPHE topology using different metals. The study proposes to fabricate lung-inspired CPHEs from metal powders such as steel, aluminum, and titanium using DMLS as an additive manufacturing method, with the same geometry and roughness. The objective is to achieve the maximum heat transfer with minimum pressure loss. The thermo-hydraulic performance of these three different CPHEs is evaluated experimentally and numerically for various operating conditions. Additionally, the performance of CPHEs made from different materials is compared to that of a chevron type brazed PHE. The study first introduces the design and fabrication of the proposed lung-inspired CPHE. The experimental testing methodology and numerical procedure is also be presented. Finally, the thermo-hydraulic performance of the lung-inspired CPHE topology made of different materials under various operating conditions is extensively discussed.

**2. Design and manufacturing of CPHE**

The design and manufacturing of the compact plate heat exchanger (CPHE) is an optimization problem where a low pressure drop should be achieved against a high heat transfer rate. Considering the small dimensions (weight and volume; e.g., mini- or micro- channel) in this problem, the manufacture becomes more complex for a long lifetime. For such a problem, the biological structure, movement and other functions of living things (animal, insect, plant) existing in nature can be solved within engineering knowledge. In Ref. [10], embossed shapes were created on the plate for a CPHE, inspired by the alveoli of the human lung [13], using a biomimetic approach. The relevant lung-pattern CPHE and its details are demonstrated in **Figure 1**. Thanks to the embossed shapes, heat transfer is increased by creating turbulence in the flow channel between the two plates. However, improving turbulence causes an increase in pressure drop due to friction.

It should be noted that unlike Ref. [10], the information presented here is the result of long-term experimental and numerical studies. As seen in **Figure 1**, six flow channels were created on the plate surface after the port inlet of the CPHE to prevent dead flow area. Alveoli-shaped fins were designed perpendicular to the flow, in the channels. The alveolar fins were equipped with a girder of 67.7 mm in length, which was slightly shorter than the width of the plate. The width of the girder at the plate surface was 0.8 mm, and the height of the girder from the plate surface was 0.3 mm. The fins were characterized by a series of open alveoli patterns. To enhance the heat transfer area and to achieve a smooth and uniform flow distribution, routers were strategically placed on the front surface of the plate. These routers were characterized by a height of 1 mm, width of 1 mm, and a length of 121.6 mm. To direct the flow, spherical barriers were placed in the front of the inlet and outlet ports. Diameters and a height of the barriers were 2 mm and 1.35 mm respectively. Resulting hydraulic diameters of the ports were 18 mm for hot side and 13 mm for cold side.

The dimensions of the CPHE, which consists of one piece in the smallest size within the technological, manufacturing and engineering limitations, were formed from 3 plates (counter-flow, single pass for hot and cold sides) measuring 74 mm x 192 mm (see **Figure 1**). The fluid flows in two non-contact flow channels formed between the two consecutive plates of heat exchanger, a hot side and a cold side. The plate thickness was designed and manufactured as 1 mm of the first and last plates and 0.7 mm of the middle plate for the 3-plate lung-pattern CPHE, on the right side of **Figure 1**. The gap between two plates was 1.35 mm. Thus, the compactness value of the CPHE is 11626 for the smallest dimensions where it ensures the flow of water in optimum conditions.

The lung-pattern CPHE designed above was obtained using direct metal laser sintering (DMLS) of AISI316-powder for stainless steel, AlSi10Mg-powder for aluminum (on the right side of **Figure 1**) and TiAl6V4-powder for titanium. Some properties of the metal powders used are listed in **Table 1**. In this study, the matching of experimental and numerical results of the CPHEs produced from three metal alloys and the effects of plate material on thermo-hydraulic performance were thus discussed. Using a fiber laser beam that traverses through a galvano-optic system and follows a path determined by stereolithography (STL) data, the DMLS process involves the controlled layer-by-layer etching of metal powders spread out on a construction platform. Precision in layered structures is directly tied to manufacturing parameters, and for structures with complex topologies like CPHEs, the manufacturing stage requires the determination of the parameters that will affect the surface heat transfer coefficient. Optimum production conditions were determined for the CPHEs produced from three different powders as a single piece. The grain size of the powders varies between 20 µm and 200 µm. A powder size of 20 µm was preferred especially for the mini- or micro-channels of the CPHE and the surface roughness of the plate.

In a DMLS process, thickness of the powder spread out on the system platform that can be etched by laser, lateral advance rate (scan speed) and the progress (scan direction) of the laser source, the intensity and the spot diameter of laser source need to be determined before processing. In this study, according to the surface roughness of the manufactured CPHEs (50 µm) power, spot diameter and advance speed of the laser source were selected as 200 W, 100 µm, and 500 mm/s, respectively. Furthermore, to simplify the manufacturing process, the CPHEs were placed at a 30° angle on the build platform. Thus, the CPHE (on the right side of **Figure 1**) could be manufactured by the DMLS method in very short time period (about 2 hours) without requiring any additional shaping processes such as turning, milling and welding and without causing any deformation and sealing problems.

**3. Experimental and numerical analyses**

Lung patterned CPHEs were manufactured using the DMLS method from three different materials as steel, aluminum and titanium as a single piece. An experimental study was carried out to discuss the effects of the material types on the thermo-hydraulic performance of the manufactured CPHEs and to ensure the accuracy of numerical analysis. For this purpose, an experimental setup was built. The schematic flow diagram of the experimental setup used is illustrated in **Figure 2**. As seen in **Figure 2**, there are two water tanks (22 L), hot and cold, in the experimental setup. 3 kW resistance and 8.7 kW evaporator (dry cooler) are used to adjust the temperature of the water in the cold water tank. A similar application is made with a 5 kW resistance in the hot water tank. Thus, the water temperature is kept constant at the desired value in both tanks. The water in the desired condition from the tanks is pressed into the heat exchanger with the help of pumps (max. 40 L/min). System flow rates in the hot and cold sides are adjusted at the desired value with the actuator valves. Their control is carried out with turbine flowmeters. Tanks and connections in the experimental setups are firmly insulated to keep the loss of heat into the environment minimized.

In the experimental setup shown in **Figure 2**, a couple of sensors is used in order to collect data from the input and output ports of the CPHE. Industry standard PT100 sensors are used for temperature sensing. The sensors have a response time of 100ms with an accuracy of ±1 °C. Operating range of pressure transmitters are between 2-1000 bar with an accuracy of ±0.25 bar. The response time is less than 5ms. With the help of PLC, the relevant data from the sensors are measured and recorded. An actuator valve and turbine flowmeter keep the flow rates of the fluid constant on the both hot and cold sides. Flow rates on the hot and cold sides have a measuring range of 3-20 L/d. It can be adjusted to the desired value with an accuracy of 0.5%. The data are received by a data logger connected to the computer. The amount of heat transferred in CPHE is utilized to account for the uncertainty of the experimental data as proposed by Kline and McClintock [14]. The measured overall uncertainty is 0.6%. This value satisfies all the criteria set out by the experimental technique.

Three different CPHEs manufactured were operated for 300 h under different operating conditions. The operating conditions were summarized in **Table 2**. Note that these conditions were also used in numerical analysis. According to **Table 2**, a uniform flow rate of 3 and 6 L/min at constant static inlet temperature was selected at the inlet ports of the CPHE. Equivalent flow rate was used on both sides to maintain the energy balance on both sides. Thus, errors that may be encountered in numerical analysis can be observed. The temperatures of the hot inlet port were set at 90 °C and 70 °C, while the temperatures of the cold inlet port were at 40 °C and 50 °C. In numerical analysis, constant pressure boundary condition was assumed at the output of the domain. All numerical simulations were run on a workstation on 32 threads. Total amount of available RAM 128 GB.

In the preliminary design and the final design after production, numerical analysis of CPHEs were performed on the Ansys-Fluent software platform [15]. For the finite volume method, analysis was considered over an entire fluid channel, including distribution areas at the inlet and outlet ports. The solution of the analysis was made by applying boundary (operating) conditions to the numerical mesh structure obtained from the flow volume models of the fluids circulating in the CPHE. In the analysis, solutions of continuity, momentum and energy equations are made independent of time. The “Pressure Based Solver” approach was used, since the phase and density changes were not large enough to affect the results [15]. Simple algorithm and Standard k-ε model were used for solution. As a first step, the convergence of the analysis was achieved by using the First Order Upwind solution method. In the next step, the Second Order Upwind solution method was used to obtain the most accurate result.

Good mesh characteristics were difficult to achieve in the CPHE due to the presence of many narrow passages. However, it is important to create the correct mesh structure in order to obtain correct results in the analysis [10]. For this reason, tetrahedral mesh elements were preferred compared to hexahedral elements because they are easier and better mesh quality and are suitable for complex geometries [16]. **Figure 3** shows the numerical mesh structure of the CPHE geometry. For the CPHE geometry, there was a 0.04% change in temperature at the port exit after 36 million mesh elements. No change was observed in Reynolds and Nusselt numbers due to a very small change in temperatures. Therefore, a total of 36 million tetrahedral mesh elements were used in CPHE geometries.

**3.1. Data reduction**

Under steady state condition where there is no phase change in fluids on hot and cold side at adiabatic and constant pressure, the heat rate of a CPHE can be calculated by the following expression.

(1)

with

(2)

(3)

where *,* ve indicate the mass flow rate, specific heat capacity and temperature, respectively. The subscript and represent hot and cold side.

For the thermo-physical properties of water, the mass average temperatures of the hot and cold side can be calculated:

(4)

(5)

where the subscript represents average. As there is a difference between heat removed () and heat absorbed () due to heat loss, the mean of total value between and () can be used in calculations.

(6)

The total heat transfer coefficient () can be calculated as follows

(7)

where is the total heat transfer area and is the logarithmic mean temperature difference between the wall and fluids on the hot and cold sides of the CPHE, as follows:

(8)

For counter flow, and , respectively, can be calculated as follows:

(9)

(10)

Because the temperatures inside a heat exchanger are variable, the temperature differences vary across the heat exchanger. This can cause confusion in the calculations. Therefore, the heat capacities of the fluids on hot and cold side can be utilized [17]:

(11)

(12)

where denotes the heat capacity for the fluids on the hot and cold side.

The effectiveness of any heat exchanger is given by [17, 18]

(13)

where is expressed as the maximum heat transfer amount, as follows

(14)

where denotes the minimum heat capacity of the fluid on hot and/or cold side. If , then , while if .

Thermo-hydraulic performance in a CPHE is based on geometry parameters, fluid and flow type. The behavior of the flow type is characterized by the Reynolds number [19].

(15)

Where and is denote the density and dynamic viscosity of fluid, respectively. In numerical analysis, the dynamic viscosity of water at 65 °C (=(90 °C+40 °C)/2) or 60 °C (=(70 °C+50 °C)/2)can be accepted. stands for fluid velocity. The following equation is used to find the velocity in the direction of water on hot and cold side.

**(16)**

where is the hydraulic diameter and it can be calculated as [18]:

(17)

where is the perimeter length.

Another important optimization parameter affecting the thermo-hydraulic performance in CPHEs is the pressure drop. When kinetic and potential energies are neglected due to the small distance between the ports, the total pressure drop (*∆P*) across the CPHE can be defined as:

(18)

where is the pressure drop due to port effect. According to Shah and Focke [20], this can be evaluated as follows:

(19)

where is the velocity of the fluid water at the inlet and is the pressure drop due to the internal structure of a CPHE. Thus, the pumping power in a CPHE can be calculated as:

(20)

where is the specific volume.

In order to comprehensively evaluate the overall performances of the CPHEs, COP can be given [11], as defined below:

(21)

**4. Results and discussion**

This study shares the results of experimental and numerical studies of the lung-inspired compact plate heat exchangers (CPHEs) (3 plates; one hot pass, one cold pass) produced by the additive manufacturing method. For this purpose, the thermo-hydraulic performance of 3 different CPHEs of the same roughness produced from material powders as steel, aluminum and titanium is evaluated for different operating conditions. The percentage error of numerical analysis results of CPHEs from experimental results for average total heat transfer in various operating conditions is listed in **Table 3**. The percentage error of the results of average pressure drop is given in **Table 4**. These results show that the numerical analysis is in good agreement with the experimental results.

**Figure 4** displays the variation of temperature difference over time in six different operating conditions for hot and cold sides of the lung patterned CPHEs made of steel (ste), aluminum (alu) and titanium (tit) materials. It is pointed out that the reason for the fluctuation in the curves is the intermittent operation of the system. **Figure 4(a)** shows the temperature difference change at a flow rate of 3 L/min on the hot side. As seen in **Figure 4(a)**, the highest temperature difference (average 23 °C) during the whole test occurs in the CPHE with aluminum material for a temperature input of 90 °C. It is followed by the steel material CPHE for 90 °C inlet with average 18 °C and the titanium material CPHE for 90 °C inlet with average 10.6 °C. From **Figure 4(a)**, the difference in inlet temperature of 70 °C for the CPHE with aluminum material is 9.5 °C. The CPHE with steel material has a difference of 8.4 °C at inlet temperature of 70 °C. For the CPHE with titanium material, the difference is 6.5 °C for 70 °C inlet. For 90 °C and 70 °C inputs, the temperature difference is closest to each other in the CPHE with titanium material. The variation of the temperature difference with time for the cold side at a flow rate of 3 L/min is presented in **Figure 4(b)**. As seen in **Figure 4(b)**, the highest temperature difference on the cold side is the CPHE with aluminum material (average 21.8 °C) for the condition of 90-40 °C. It is followed by the CPHE with steel material at 14.4 °C and the CPHE with titanium material at 9.6 °C under the same condition. Regarding to **Figure 4(b)**, for the CPHE with aluminum material, the temperature difference at 70-50 °C condition is 9.2 °C. It is 6.3 °C for the CPHE with steel material and 4.6 °C for the CPHE with titanium material at 70-50 °C. It is observed that there is a temperature difference close to each other in the CPHEs with steel and titanium materials. Comparing **Figures 4(a) and (b)**, the CPHE in which the temperature difference values on the hot and cold sides are closest to each other is the CPHE with aluminum material. The highest difference change in the hot and cold sides occurs in the CPHE with steel material at 90-40 °C.

The temperature difference change at a flow rate of 6 L/min on the hot and cold sides is displayed in **Figures 4(c) and (d)**, respectively. In **Figure 4(c)** for hot side, the highest average temperature difference is 25.1 °C for the 90-40 °C condition in the CPHE with aluminum material. It is followed by the CPHE from steel with 20.7 °C and the CPHE from titanium with 19 °C under the same condition. The average temperature difference at 70-50 °C condition is 8.6 °C for the CPHE with aluminum, 7.6 °C for the CPHE with aluminum, and 8.1 °C for the CPHE with titanium. **Figure 4(d)** presents the temperature difference variation on the cold side. It is observed in **Figure 4(d)** that the temperature difference changes in **Figure 4(c)** decrease as the flow rate increases. Especially in 90-40 °C conditions, there is a great drop. From **Figure 4(d)**, the highest temperature difference is ranked as the CPHE with aluminum (average 18.5 °C) at 90-40 °C, the CPHE with steel (average 12 °C) at 90-40 °C and the CPHE with titanium (average 7.1 °C) at 90-40 °C. Except for 6 L/min on the hot side at 70-50 °C, the temperature difference in the titanium CPHE is lower than those of the other CPHEs. In addition, for **Figures 4(a) and (c)**, the temperature difference on the hot side rises with the increase of flow rate in all CPHEs. An opposite trend is observed for **Figures 4(b) and (d)** on the cold side.

As a result of the CFD analysis, the temperature, pressure and velocity contours of the PIDs were obtained for different operating conditions. **Figure 5** shows the temperature distributions on the hot and cold sides of the CPHEs at the temperature inlets of 90-40 °C. **Figures 5(a) and (b)** are used for flow rates of 3 L/min and 6 L/min, respectively. It is seen from **Figure 5(a)** that hot and cold fluids show homogeneous distribution on the plate surface thanks to the 6 guide channels on the plate. For the CPHEs of titanium, steel and aluminum, the exit temperature of the hot side is 78.68 °C, 70.5 °C and 65.9 °C, respectively. The exit temperature of the cold side is 50.6 °C, 55.8 °C and 62.7 °C, respectively. The maximum temperature variation is 24.1 °C on the hot side and 22.7 °C on the cold side, in the CPHE with aluminum material. For 6 L/min, in **Figure 5(b)**, the CPHE with aluminum material shows greater temperature variation on both the hot and cold sides than at 3 L/min. The temperature difference of the hot and cold sides is 21.1 °C and 12.9 °C for steel, 25.5 °C and 18.5 °C for aluminum, and 15.8 °C and 11.7 °C for titanium, respectively. Regarding to **Figure 5**, dead zones are formed on the edge of the plate by gravity at the water outlet on the cold and hot sides. In these regions, heat transfer is low due to the slow fluid velocity. This is evident on the hot and cold sides of the titanium CPHE.

In **Figure 6**, the temperature changes of the hot and cold sides are given for the 70-50 °C condition. In **Figure 6(a)** at 3 L/min, the presence of the greatest temperature variation on the hot and cold sides is observed in the CPHE with aluminum material. The hot side and cold side exit temperatures of the steel CPHE are 61.1 °C and 56.6 °C, respectively. These are 60.2 °C and 59 °C for aluminum and 63.7 °C and 54.5 °C for titanium, respectively. The most temperature variation occurs on the aluminum CPHE, with 9.8 °C for the hot side and 9 °C for the cold side. For 6 L/min given in **Figure 6(b)**, in the steel CPHE, water leaves the plate at 62 °C on the hot side and 54.6 °C on the cold side. Thus, the temperature difference is 8 °C and 4.6 °C for the hot and cold side, respectively. This is 8.2 °C and 7.6 °C for aluminum and 7.9 °C and 3.1 °C for titanium, respectively. It is observed that aluminum has the highest differences and titanium has the lowest differences.

The pressure field distribution of the hot and cold side of the CPHEs with different materials at an inlet temperature condition of 90-40 °C is indicated in **Figure 7**. **Figure 7(a)** is prepared for a 3 L/min flow rate. The pressure variation on the hot fluid side is 28,179 Pa for steel, 28,318 Pa for aluminum and 28,642 Pa for titanium, respectively. On the cold fluid side, this is achieved as 20,275 Pa for steel, 20,309 Pa for aluminum and 20,664 Pa for titanium. It is observed that the pressure drop is the least in the steel material CPHE. On the other hand, the highest pressure drop is achieved with the use of titanium material. The pressure distribution at 6 L/min flow rate is given in **Figure 7(b)**. Looking at **Figure 7(b)**, the pressure contours are approximately the same for the hot side when using three different materials. The pressure drops using steel, aluminum and titanium are 92,997.3 Pa, 92,662 Pa and 92,961.7 Pa, respectively. On the cold side, the pressure drops for steel, aluminum and titanium are 71,835.6 Pa, 70,097.2 Pa and 65,434.8 Pa, respectively. It is observed that the pressure drop for the cold side of the CPHE with titanium material is less than those of other CPHEs. On the hot side, it happens in the aluminum CPHE. From **Figures 7(a) and (b)**, it is observed that the pressure drop increases as the flow rate increases. The pressure drop increases as the velocity starts to increase in the same flow channel [21]. Kim *et al.* [22] proposed increasing the distance between the plates to reduce the pressure drop in CPHEs.

The pressure contours on the hot and cold sides for temperature inputs of 70-50 °C are given in **Figure 8**. For a flow rate of 3 L/min in the CPHE with steel material, in **Figure 8(a)** the pressure drop for the hot side is 25,674.8 Pa, while it is 17,226.6 Pa for the cold side. For aluminum material, the pressure drops of the hot and cold side are 28,425 Pa and 19,216 Pa, respectively. For titanium, they are 23,186 Pa and 15,926 Pa, respectively. CPHE with the least pressure drop on the hot and cold sides is made of titanium material. As can be seen in **Figure 8(b)**, the pressure drop variation on the hot and cold side is presented for 6 L/min flow rate. The pressure drop of the hot and cold side is, respectively, 99,006 Pa and 71,306 Pa for steel, 96,951.8 Pa and 68,312 Pa for aluminum, and 97,367.7 Pa and 72,021 Pa for titanium. In the context of **Figure 8(b)**, it is seen that the pressure drop on the hot and cold sides is less when using aluminum material. When **Figures 7 and 8** are compared, in general, less pressure drop is observed at 70-50 °C condition (difference of 20 °C) for 3 L/min flow rate, while it was at 90-40 °C condition (difference of 50 °C) for 6 L/min.

In CPHEs, the higher the fluid velocity, the higher the pressure drop [21]. Thus, it causes an increase in pumping costs. However, it is important that the flow in the hot and cold flow channels in the CPHE is homogeneous. Dead zones, where the flow is close to zero, also pose a problem for heat transfer. The velocity counters of the hot and cold sides are presented in **Figure 9**, for the 90-40 °C condition. As can been in **Figure 9(a)** at 3 L/min, the hot side fluid velocities for steel, aluminum and titanium are very close to each other. On the hot side, the penetration velocity of the fluid into the plate in CPHEs in all materials is about 2 m/s. On the cold fluid side, when steel material is used, it is observed from the figure that the flow rate on the plate surface is higher than the others. In the steel material, while the fluid enters the plate with approximately 2.2 m/s, it is approximately 1.8 m/s in the middle of the plate and approximately 2.5 m/s by accelerating at the exit. In aluminum and titanium materials, velocity contours are almost close to each other. **Figure 9(b)** gives velocity contours on the hot and cold side for a flow rate of 6 L/min. For all three plate materials, the inlet velocity of the hot side fluid is about 3 m/s, while the velocity at the exit (4.5 m/s) has increased again. When the fluid flow rate increases, it is determined that the velocities on the hot side are higher than those on the cold side in 3 CPHEs. From **Figure 9(b)**, the fluid on the cold side entered the plate at about 3.3 m/s and increased to about 4 m/s at the exit.

The velocity counters of the hot and cold sides are indicated in **Figure 10** for the temperature condition of 70-50 °C. **Figure 10(a)** shows the velocity contours obtained from the analyzes at a flow rate of 3 L/min with three different materials. For all three CPHEs on the hot side, the inflow of the fluid to the plate is about 1.5 m/s, while the fluid inlet on the cold side is about 2 m/s. While the fluid velocity on the plate surface is about 1.3 m/s in the use of aluminum material and about 0.5 m/s in the use of steel material, the fluid velocity (about 0.3 m/s) in titanium is the lowest. On the cold side, the fluid velocity at the plate surface is approximately the same for each CPHE. The velocity increases at the cold fluid outlet. In **Figure 10(b)** for a flow rate of 6 L/min, at the three CPHEs on the hot side, the velocity of the fluid at the plate inlet is about 3 m/s and on the cold side about 3.5 m/s. Since the plate geometry and flow rate are the same for the hot side and the cold side comparing **Figure 9 and 10**, the same velocity profiles are observed along the flow direction. This phenomenon was reported by Göltaş *et al.* [10], Gürel *et al.* [16], and Gut *et al.* [23]. In this study, it can be reported that the use of different materials has little effect on pressure drop and velocity in CPHEs with the same geometry. This small effect may be due to the density and different specific heat capacity for different materials.

**Figure 11** demonstrates the change in average total heat transfer over time under various operating conditions for different CPHE materials. The fluctuation in the graphics is the result of intermittent operation during the 300-hour experiment. Therefore, as a result of the experimental study, **Figures 11 (a), (b) and (c)** are drawn for steel, aluminum and titanium, respectively. As can been in **Figure 11(a)**, the maximum average heat transfer was obtained as approximately 6,848 W at 90-40 °C and 6 L/min conditions. In the same conditions, it is about 6,157 W in the chevron type brazed PHE (che). The lung-pattern CPHEs use three plates while the che has six plates. The heat transfer rates for 3 L/min and 6 L/min conditions at 70-50 °C are approximately 1,536 W and 2,453 W, respectively. In **Figure 11(b)** for aluminum, among other materials, it is observed that the average heat transfer rate is maximum with 9,115 W at 90-40 °C and 6 L/min. It is 2,958 W more than the heat transfer rate of the che under the same conditions. At 3 L/min, it is 4,687 W. For 70-50 °C, the heat transfer rate is obtained as 1,949 W and 3,285 W, respectively, at 3 L/min and 6 L/min flow rates. Regarding **Figure 11(c)**, the heat transfer rate of the CPHE with titanium is maximum (5,462 W) at 90-40 °C and 6 L/min conditions. Its heat transfer remained below the value of the che under all conditions. The heat transfer rates for 3 L/min and 6 L/min conditions at 70-50 °C are approximately 1,157 W and 2,280 W, respectively. I can be observed from all figures that the average total heat transfer rate increases with the use of high fluid inlet temperature and high flow rate. The aluminum material CPHEs transfer more heat than the steel and titanium material CPHEs and also the chevron type brazed PHE.

The variation of pressure drop versus time is given in **Figure 12**. As can be seen in **Figure 12(a)** for ste, the highest pressure drop occurs at the chevron type brazed PHE (che) for both flow rates. It is 23.2 kPa at 3 L/min and 89.2 kPa at 6 L/min. The lowest pressure drop is 17.9 kPa and 84.2 kPa at 3 L/min and 6 L/min for 70-50 °C, respectively. In **Figure 12(b)** for alu, the pressure drop under all conditions exhibits above that of CHE. The pressure drop of aluminum material is higher compared to that of steel material. The highest pressure drop is achieved at 90-40 °C - 6 L/min. It is then followed by the 70-50 °C - 6 L/min condition. Regarding to **Figure 12(c)**, the pressure drop at all conditions of tit, such as ste, is below the pressure value of the chevron type brazed PHE (che). The lowest pressure drop occurs at 90-40 °C for 6 L/min and at 70-50 °C for 3 L/min. They are 79.5 and 13.4 kPa, respectively. The pressure drop variation for the same geometry is due to the friction factor and the effects of the density and velocity of the fluid. Comparing the graphs in **Figure 12**, the lowest pressure occurs in the CPHE with titanium material.

**Figure 13** presents the variation of CPHE effectiveness over time under different operating conditions. The effectiveness of lung-patterned CPHEs and the chevron type brazed PHE over time for the 90-40 °C condition is given in **Figure 13(a)**. Looking at the figure, it is seen that the CPHE with aluminum material (alu) has the highest effectiveness in both flow rates. They are 0.448 and 0.436 at 3 L/min and 6 L/min, respectively. It is followed by steel material (ste) one with 0.325 and 0.327 for the respective flow rates. With an effectiveness of 0.294 at 6 L/min, the chevron type brazed PHE (che) has lower effectiveness than CPHEs with aluminum and steel materials. The effectiveness of CPHE with titanium material (tit) is 0.201 at 3 L/min and 0.261 at 6 L/min. And the chevron type brazed PHE (che) has the lowest effectiveness in 3 L/min. In **Figure 13(b)** for 70-50 °C, there are similar results observed in **Figure 13(a)**. It is noted that the effectiveness of the chevron type brazed PHE (che) in **Figure 13(b)** is used at 90-40 °C. As per **Figure 13(b)**, the effectiveness of the CPHE with aluminum material (alu) is 0.466 at 3 L/min and 0.392 at 6 L/min. At 3 L/min and 6 L/min, the effectiveness is 0.367 and 0.293 for the steel material (ste), and 0.276 and 0.272 for the titanium material (tit), respectively. It is observed from **Figures 13(a) and (b)** that the effectiveness values are even higher as the temperature difference on the hot and cold sides decreases.

The variation of COP values of CPHEs made of different materials for different operating conditions is shown in **Figure 14**. The COP decreases as the flow rate increases. It thus indicates that the pressure drop has a significant effect on the COP. Steel material CPHE always has the largest COP for 90-40 °C - 3 L/min condition; which means outstanding overall performance. It is followed by alu, tit and che. This order does not change for 90-40 °C - 6 L/min. Their COP values approach each other. As shown in **Figure 14**, when the operating condition is 70-50 °C - 3 L/min, the COP of the titanium material CPHE is greater than the other two. In 70-50 °C - 6 L/min, the highest COP value is in the CPHE with aluminum material. In addition, as mentioned earlier in **Figures 11 and 13**, the CPHE with aluminum material exhibits superior heat transfer rate; however, the high pressure drop is a disadvantage. This means the attenuating effect of pressure drop on thermal performance.

**5. Conclusion**

In this study, the thermo-hydraulic performances of the lung-inspired compact plate heat exchangers (CPHEs), which have the same geometry and roughness, produced by the additive manufacturing method from different material powders, are investigated experimentally and numerically. The CPHEs are manufactured from steel, aluminum and titanium powders in 50-micron size. In order to compare the performance, 300 hours of experiments are carried out under different operating conditions. In experiments and numerical analysis, pure water is used as a fluid in single phase and is passed at the same flow rate on the hot and cold sides. Numerical analysis is used to understand the flow and heat transfer mechanisms within CPHEs. Thus, the most general conclusions listed below can be reached:

* + Errors not exceeding 2.2% were observed between the numerical and experimental results for the heat transfer of the CPHEs under different operating conditions. There was a good agreement between them. In the average pressure drop, the errors were at most 44%. For this, the results of the experimental study were considered.
  + In all CPHEs, the heat transfer rate and pressure drop increase as the inlet temperature difference of the hot and cold side and the flow rate increase. The temperature distributions for the cold and hot sides are homogeneous. The aluminum material CPHE provided better heat transfer than the chevron type brazed PHE in all operating conditions. An improvement in heat transfer of 75.2% and 11.2% was achieved at 3 and 6 L/min for 90-40 °C, respectively, compared to that of the chevron type brazed PHE.
  + The highest heat transfer rate in all operating conditions occurs in the CPHE with aluminum material. At 3 L/min, the heat transfer rate was 4,687 and 1,949 W for 90-40 °C and 70-50 °C, respectively, while at 6 L/min they were 9,115 and 3,285 W. The CPHE with aluminum material was the highest effectiveness as 0.466 at 3 L/min and 0.392 at 6 L/min. Therefore, its heat transfer performance was superior.
  + The pressure drop of the chevron type brazed PHE (23.2 kPa) was the highest under all operating conditions except for the CPHE with aluminum material (27.1 kPa). The lowest pressure drop occurred in CPHE with titanium material (13.4 kPa). Although the CPHE with aluminum material in same geometry has the best heat transfer performance, it had the worst results for pressure drop. Compared to the chevron type brazed PHE, the pressure drop of the CPHE in titanium material was reduced by 31.8% and 10.9% at 3 and 6 L/min for 90-40 °C, respectively.
  + COP performance () was higher in all the CPHEs compared to the chevron type brazed PHE at operating conditions of 3 and 6 L/min at 90-40 °C. The CPHE with aluminum material exhibited superior heat transfer rate compared to other CPHEs. However, a low pressure drop occurred. This resulted in the debilitating effect of the pressure drop on performance. Compared to the others, the steel material CPHE showed a better COP performance.

The results presented here indicated that the evaluation of materials with different thermal conductivity in CPHEs using their complex internal geometric properties at small sizes can be considered as a highly promising alternative solution for high heat transfer and low pressure drop. Thus, it is observed that the material is as effective as the geometry in the performance of a compact heat exchanger. In addition, this study can guide the selection of materials in the production process of heat exchangers with additive manufacturing methods.

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**Nomenclature**

|  |  |
| --- | --- |
| A | Heat transfer area [m2] |
|  | Specific heat capacity [J/kgK] |
|  | Heat capacity [W/K] |
|  | Coefficient of performance [-] |
|  | Hydraulic radius [m] |
|  | Thermal conductivity [W/mK] |
|  | Mass flow rate [kg/s] |
|  | Pressure [Pa or kPa] |
|  | Power rate [W] |
|  | Perimeter length [m] |
|  | Heat rate [W] |
|  | Reynolds number [-] |
|  | Temperature [K] |
|  | Overall heat transfer coefficient [W/m2K] |
|  | Velocity [m/s] |

*Greek Letters*

|  |  |
| --- | --- |
|  | Differential difference [-] |
|  | Effectiveness [-] |
|  | Density [kg/m3] |
|  | Dynamic viscosity [Pa s] |
|  | Specific volume [m3/kg] |

*Subscripts*

|  |  |
| --- | --- |
|  | Average |
|  | Cold |
| CPHE | Compact plate heat exchanger |
|  | Hot |
| in | Input |
| out | Output |
| lmtd | Log mean temperature difference |
| max | Maximum |
| min | Minimum |

*Abbreviations*

|  |  |
| --- | --- |
| alu | Aluminum |
| che | Chevron |
| CPHE | Compact Plate Heat Exchanger |
| DMLS | Direct Metal Laser Sintering |
| PHE | Plate Heat Exchanger |
| PLC | Programmable Logic Controller |
| ste | Steel |
| STL | Stereolithography |
| tit | Titanium |

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