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METHODOLOGY FOR OBTAINING 3D CAD MODELS FROM COMPLEX OBJECTS THROUGH DIGITIZATION AND NUMERICAL ADJUSTMENT: HEAT EXCHANGER PLATES

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Abstract. Digitizing is an applied approach to obtaining complex geometries, especially for surfaces that have free shapes. This is a non-contact, non-destructive technique that generates a cloud of points in a coordinate system that accurately describes the size and shape of the physical object. However, for some more complex geometries, the result obtained through three-dimensional scanning is not yet suitable for some applications such as numerical simulation. In this study, a three-dimensional (3D) scanner was used to obtain the CAD model of the plate of a gasketed plate heat exchanger (GPHE). The analyzed plates have a thickness of 0.7 mm and their handling promotes distortions in the piece and deformations that are undesirable for further analysis. In this way, a numerical simulation applying the finite element method (FEM) was performed after the generation of the geometry through scanning to promote alignment of the geometry, thus correcting the deformations present in the physical part that was captured by the scanner. As a result of the numerical treatment, the geometry that had a deformation of 2.43 mm at its maximum point, in relation to a flat reference surface, now presents a uniform height, reducing this distance to approximately zero. The interaction between the contact points of the auxiliary flat surfaces for the alignment of the geometry and the plate, caused a maximum penetration of 0.22 mm, thus resulting in a variation of $\pm 7.5\%$ in the standard height of the plate, which is 3.2 mm. The scanning methodology, the treatment of the point cloud resulting from the scanning and the geometry alignment applying FEM are described in this article. The CAD model obtained from the heat exchanger plate shows that numerical simulation can help in obtaining a computational domain that is representative of the real object and suitable for future analysis in several applications.

Keywords: CAD, Numerical Simulation, FEM, Scanner 3D, metrology

1. INTRODUCTION

Computer-aided design (CAD) is an important tool for tridimensional numerical analysis based on Computational Fluid Dynamics methods (CFD) and structural analysis methods (FEM). For some analysis, a highly complex geometry must be applied and even small uncertainties may result in significant deviations in the data obtained from these numerical studies. Even with the advance of 3D digitizing from scanners, some cases may still suffer from small deviations encountered in the digitized CAD geometry derived from equipment uncertainties, the complexity of the geometry, or even intrinsic small undulations due to the storage or handling process. One of these cases is the 3D digitizing of thin heat exchanger plates for applications in Gasketed Plates Heat Exchanger (GPHE) applied to the oil and gas industry. This type of heat exchanger is composed of a pack of dozens or hundreds of similar thin plates pressed together in a pack, with plates ranging from 0.5 m to more than 3 m in length combined with a thickness of 0.5 mm to 0.7 mm, as can be seen in Figure 1 for a small pack of 6 plates. In Figure 1, the blue color and arrows represent the cold channel created between two plates pressed together and the red color arrows represent the hot channel. The hot and cold fluids do not mix due to the use of a gasket on each side of each plate that isolates the fluids, represented by the black line on each plate surface.

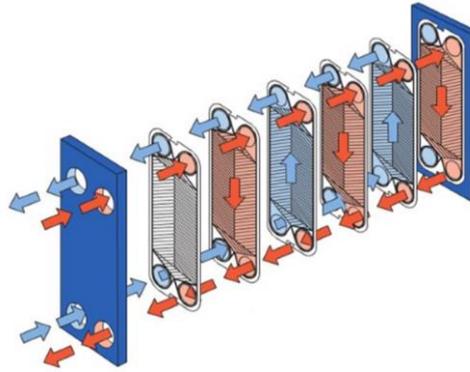


Figure 1. Fluid flow diagram in a GPHE. Adapted from Alfa Laval (2021).

A GPHE plate can have different configurations depending on parameters such as the chevron angle, length, thickness, configuration of the distribution region, and others. An image of the plate configuration analyzed in this study is represented in Figure 3 and Table 1, where its corrugation angles (the chevron angle - β_1 and β_2) can be seen together with its main dimensions and the gasket position. Considering the complexity of the corrugations of the surface of the plate 3D digitizing is one of the main methods applied to generate a CAD geometry for numerical analysis. However, due to the elevated length of the plate and its small thickness, is common that even brand-new plates present small undulations in relation to the normal plate of the plane caused by storage or handling after the manufacturing process is completed. These deviations are small reaching an order of a few millimeters in some regions of the plate. During the 3D digitizing process these deviations from the original geometry are incorporated into the 3D CAD result. For the creation of a domain for numerical simulations, at least two CAD plates must be allocated in front of one another with a uniform separation distance, for example, of 0.6 mm between plates. The deviations propagated to the CAD geometry cause this separation distance to reach an order of a few millimeters and consequently, this affected the results of the numerical analysis for thermal, fluid, and structural parameters like friction factor between plates, Nusselt number, and structural tension. Figure 2 illustrates this problem where box (a) shows the correct separation distance (shown in Figure 2 (a)(2)) occasioned by the positioning of a correct CAD (shown in Figure 2 (a)(1)) and the incorrect separation distance (Figure (b)(4)) resulting from the positioning of a CAD geometry with a deviation (Figure 2 (b)(3)). For the operation of the heat exchanger, these undulations on the plates due to storage and handling are not present. They are corrected during the assembling process of the heat exchanger since each plate is then pressed against each other to form the pack and the small undulations are then realigned.

This effect of small undulations on the numerical results for fluid flow was described by Jafari et al. (2022). They have shown that a slight uniform increase in the separation distance between plates of a GPHE for three geometries of the order of less than a millimeter in a CFD numerical model resulted in deviations of 15%, 22%, and 43% in the friction factor calculated for each case. The smallest deviation was encountered for the case that maintained a separation distance similar to the one encountered in the real equipment.

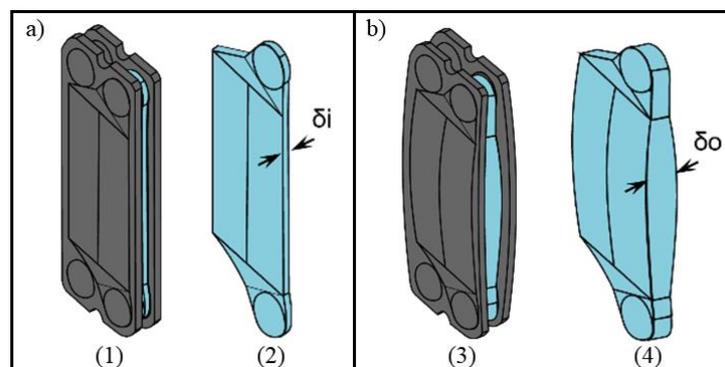


Figure 2. Numerical assembly of plates scheme: (a) plates with no deviation from the original geometry and resulting fluid domain, and (b) plates with deviation and resulting fluid domain. Adapted from Donati (2023).

It is interesting to notice that after assembly, the pack of plates of the heat exchanger also experiences an interaction between the fluid and the structure of the plates during operation that has as effect the change in the fluid and thermal parameters of the heat exchanger. Different authors have documented this effect with experimental analysis in GPHE for a range of operational conditions. Ahn and Kim (2016), Lychakov et al. (2017), and Matyash, Lychakov and Zakira

(2022) identified this effect when comparing measurements of pressure loss on the equipment for the cold and hot channels for various Reynolds numbers. They indicated that the pressure loss in the channel with less pressure is higher than the pressure loss in the channel with higher pressure, suggesting that the plates have their separation distance during operation modified depending on the conditions of the fluid in each channel. The same behavior was documented by Martins et al. (2022) for an experimental setup for structural analysis of packs of plates of GPHE and by Strobel (2023) for the fluid and thermal behavior of a GPHE. This contributes to indicate that even small deviations on the CAD of the plate from the original geometry are significant for numerical analysis results simulating the operational behavior of the heat exchanger. The objective of this work is to present a methodology combining 3D digitizing and Finite Element Modeling to obtain the CAD of a plate of GPHE and reduce its deviations from the original geometry of the plate caused by storage and handling, resulting in a CAD geometry to be used in numerical modeling in conditions more likely to the operational ones.

2. METHODOLOGY

2.1 Plate geometry

The corrugated plate used in this study has two combined Chevron angles, dividing the effective heat transfer area into four quadrants, as shown in Figure 3. The plate is referred to as High Beta Angle (H) and has distinct combinations of Chevron angles. The angles of the corrugations in quadrants 1 and 4 are equal, the same is repeated for quadrants 2 and 3, as can be seen in Figure 3 (b). Table 1 presents the main dimensions that define the H-plate.

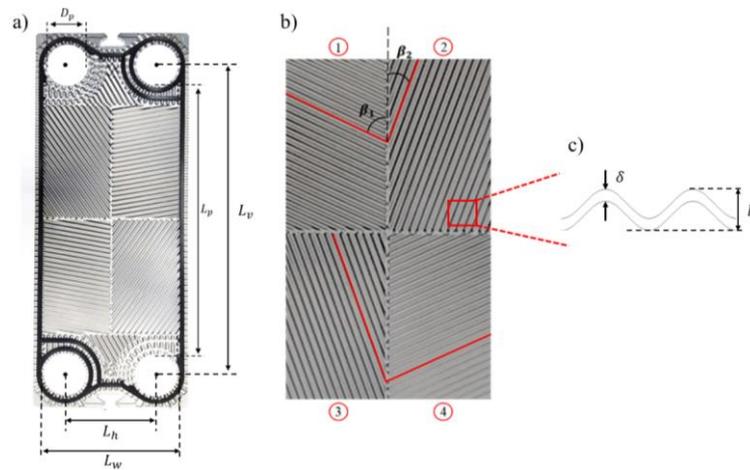


Figure 3. Four-quadrant corrugated plate: a) complete plate, and b) angle of the corrugations. Source: Adapted from Strobel (2023).

Table 1. Geometric parameters of the H-plate.

Geometric parameters	Dimensions
Average Chevron Angle ($\bar{\beta}$)	52.5°
Corrugation amplitude (b)	3.20 mm
Plate thickness (δ)	0.70 mm
Horizontal distance between gaskets (L_w)	350.0 mm
Horizontal distance between ports centers (L_h)	225.0 mm
Vertical distance between ports centers (L_v)	780.0 mm
Minimum vertical distance between ports (L_p)	675.0 mm
Diameter of the ports (D_p)	105.0 mm

Combining the H-plates results in different configurations with distinct wave patterns. In this work, the aim is to make the CAD of the H-plate, which can later be used to obtain the fluid volume for the different plate mounting combinations, which is not the focus of this work.

2.2 Scanning steps

The methodology applied in this work can be summarized in Figure 4 and consists of the following steps: (1) The corrugated plate without the gasket was painted with matte paint. (2) Uniform painting over the entire corrugated plate; (3) The plate was screwed over a wooden board; (4) The targets were positioned obeying the necessary spacing over the plate; (5) The plate was scanned using a 3D scanner model AMETEL CreaformHandyScan 3D Silver; (6) The scanned corrugated plate was treated and the point cloud transformed into a surface using the VXmodel software; (7) In the program Ansys DesignModeler the surface of the scanned plate was positioned over two auxiliary surfaces; (8) Mechanical simulation to align the corrugated surface was performed with Ansys Mechanical program; (9) The result of the mechanical simulation was the aligned surface of the corrugated plate in the form of a point cloud with a smaller size; (10) The point cloud of the aligned corrugated plate was refined using Ansys SpaceClaim program; (11) The point cloud of the aligned corrugated plate was converted to a surface using VXmodel software; (12) The gasket and inlet and outlet tubes were drawn with Ansys DesignModeler software on the surface of the aligned corrugated plate; (13) The plate was replicated, overlaid, and assembled according to the manufacturer's assembly instructions, and the fluid channel was extracted to the desired configuration using Ansys DesignModeler software.

2.3 Step 1 – Scanning and CAD generation

The three-dimensional geometry of the H-plate was obtained by scanning the plate. For this purpose, the plate was painted a matte gray color to inhibit light reflection, making it easier for the laser to capture the points during scanning. Then, the H-plate was screwed to a wooden plate in several points, approximately 40 screws of 2.5 mm diameter were used to fix the H-plate to reduce the deformation of the corrugated plate. The screws were applied at the lowest points of the corrugated plate in relation to the wooden plate, thus preserving the geometric patterns of the heat exchanger plate, as shown in Figure 5.

The 3D Scanner model AMETEL CreaformHandyScan 3D, with a resolution of 0.030 mm, available in the metrology laboratory (METEQ) at UFSC-CTJ, was used to scan the plate. The scanner used has a laser scale that uses targets positioned on the part to guide the process of obtaining the geometry (Figure 6 (a)). The targets were arranged on the plate to cover the screws in the corrugated sections and in the areas where the geometry is simpler (points 1, 2, and 3), as can be seen in Figure 6 (b). On the distribution section and sides of the plate, where the geometry is more complex, the screws were left visible (points 4, 5, 6, and 7), making it possible to obtain the geometry at these points, because the size of the targets would cover up the geometric details in this region. The scanning process was performed by passing the scanner several times over the plate, the scanner was also held at different angles to ensure the capture of geometric details. Figure 6 (c) shows the scanning of the corrugated plate.

The mesh resulting from the scanning exceeds 18 million elements, with resolution, and quality enough to allow the reproduction of the H plate with accuracy for the numerical analyses. The mesh treatment obtained through the scanning was performed with the VXmodel software. The deformations caused in the mesh by the screws and targets were removed point by point and the edges of the H-plate were smoothed, see Figure 7. Finally, the point cloud was converted into a surface.

2.4 Step 2 – mechanical alignment of the CAD

With the result of the digital scanning, the CAD of the plate still presents a warping and/or deformations inherent to the low thickness of the plate that provides warping of the original geometry, as can be seen in Figure 8, where it is possible to observe that the center of the plate presents a greater distance with respect to the lower horizontal plane than at the ends of the plate. It is noteworthy here, that even with the use of more screws to reduce the deformation of the geometry during the scanning, the warping is present in the result of the digital scanning, reaching a value of 2.43 mm in the region of greatest warping (central).

The corrugated surface resulting from the scan was aligned using FEM with Ansys Mechanical. Two auxiliary planar surfaces with a rectangular shape and slightly larger dimensions than the corrugated plate, 990 mm long and 420 mm wide, were drawn. The corrugated surface was positioned between the two auxiliary planar surfaces, as shown in Figure 8. The surfaces were positioned so that a single point of contact between the corrugated surface and the lower auxiliary planar surface was created. Thus, generating a point that was used to fix the corrugated surface, preventing rotation of the corrugated geometry during the mechanical simulation.

The displacement of the corrugated surface was kept free in the y direction and locked in the x and z axes. The lower auxiliary surface was fixed in its position. While for the upper auxiliary surface, zero displacements were set in the x and z directions, and a fixed displacement in y. The value of this displacement was determined by subtracting the distance between the flat auxiliary surfaces ($a = 12$ mm) from the amplitude of the corrugated plate ($b = 3.2$ mm), thus preserving the amplitude of the corrugation. Note that the value of a may vary depending on the degree of deformation of the corrugated surface, starting from the point of contact between the corrugated surface and the lower auxiliary surface to the position at which the upper auxiliary surface does not touch the corrugated surface.

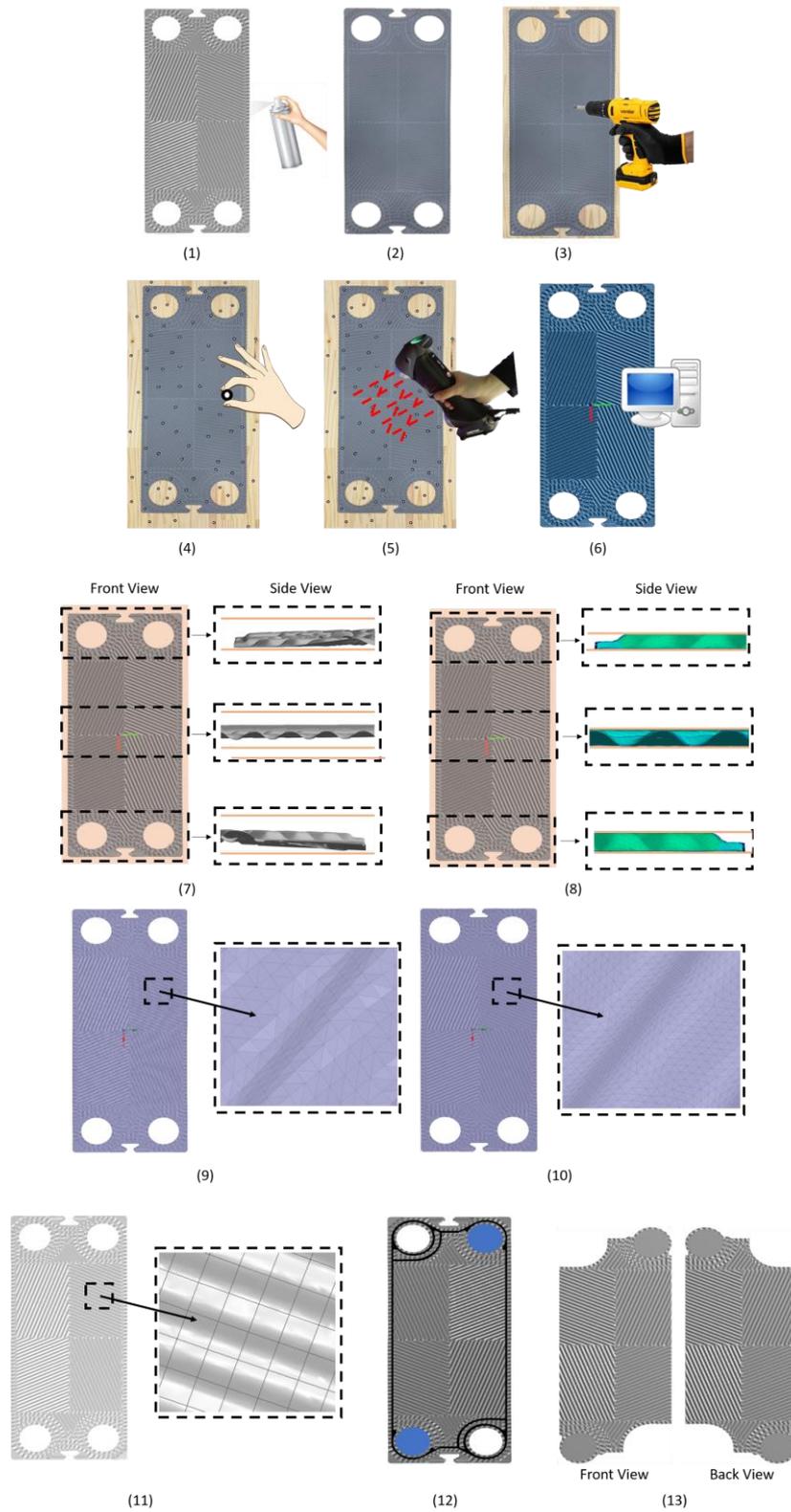


Figure 4. Summary of the methodology applied to obtain the computational domain.

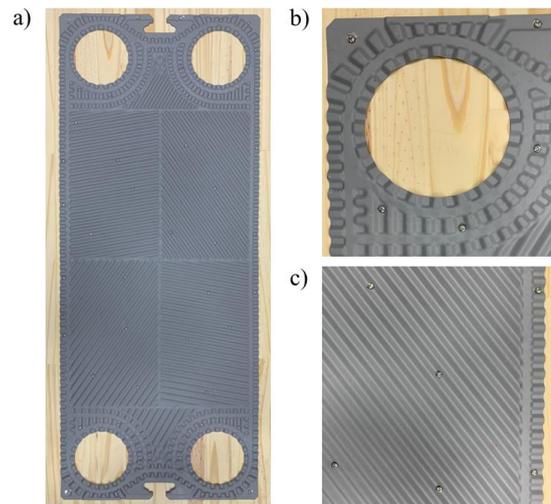


Figure 5. Corrugated plate fixed to the wood board: a) complete plate fixed, b) fixing the distribution section, and c) fixing the corrugated section.

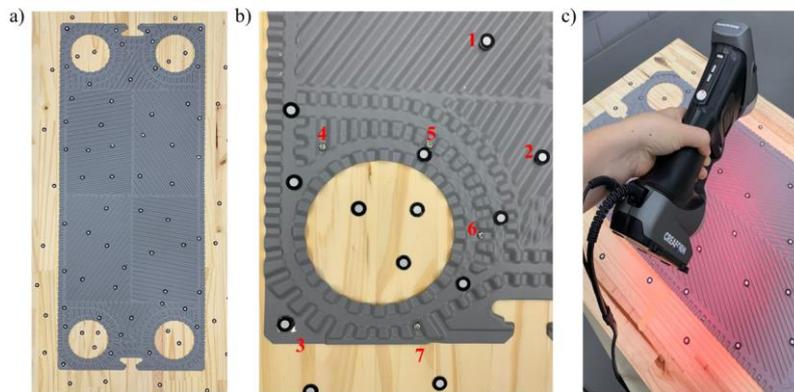


Figure 6. Positioning of the targets on the corrugated plate: (a) entire plate, and (b) in the distribution section.

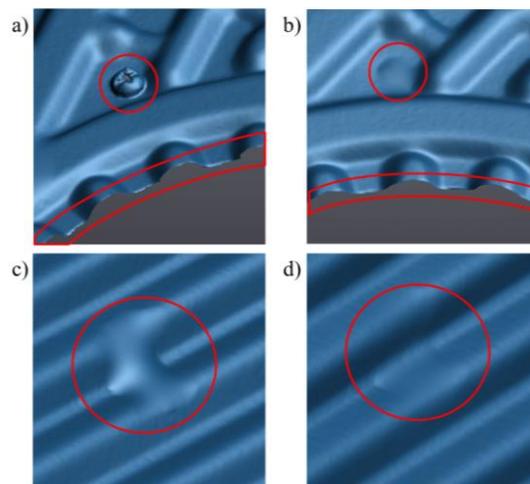


Figure 7. Treatment of the mesh obtained by scanning the plate: (a) a screw mark and non-uniform edge; (b) the screw mark removed and the edge smoothed; (c) a target mark on the corrugated section; and (d) the target mark removed.

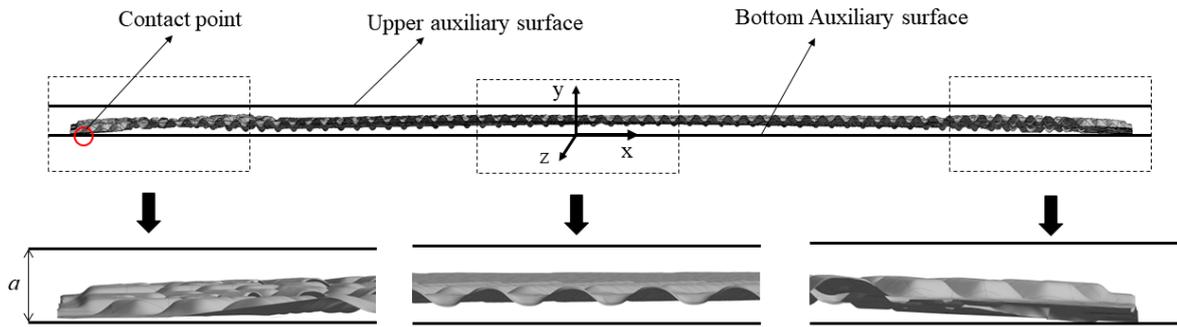


Figure 8. Schematic of the flat surfaces for corrugated surface alignment.

The contact conditions between the auxiliary surfaces and the corrugated surface were defined as frictionless. A virtual thickness of 0.1 mm was applied for the corrugated surface, giving a higher flexibility for the H-plate, and for the auxiliary surfaces, a virtual thickness of 10 mm was defined, thus giving a higher strength to deformation. Structural steel was applied as the material for all surfaces, considering the mechanical properties provided in the Ansys Mechanical library. Furthermore, a mesh of approximately 631,000 elements was applied to the H-plate and both the upper and lower auxiliary surfaces.

The resulting mesh from the mechanical simulation was refined using Ansys SpaceClaim from approximately 385,000 to 1.5 million elements for the H plate. The mesh refinement was necessary for the conversion of the point cloud to the surface in VXmodel, as the software requires a minimum number of points to perform the treatment. Finally, using Ansys DesignModeler, the gaskets were designed to limit the volume occupied by the fluid to the H-plate surface, as shown in Figure 9, finalizing the CAD of the geometry without the warping and ready for use in structural and thermofluidynamics numerical simulations.

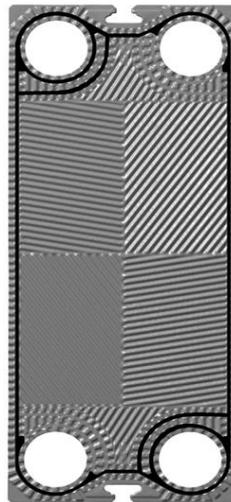


Figure 9. Aligned geometry of the four-quadrant corrugated plate H.

3. RESULTS AND DISCUSSION

3.1 Mechanical alignment of the CAD

Figure 10 shows the comparison between the corrugated plate surface obtained after scanning (Figure 10 (a)) and the one resulting from the mechanical simulation performed to align its geometry (Figure 10 (b)).

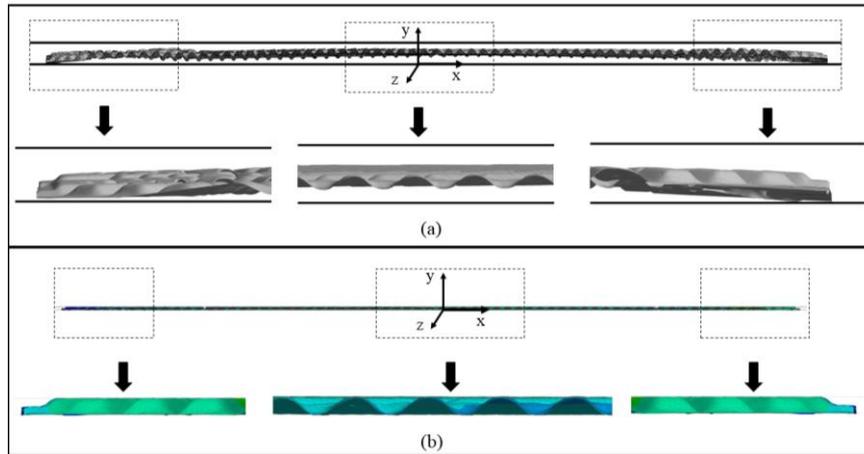


Figure 10. Corrugated surface: a) resulting from scanning, and b) resulting from alignment through mechanical simulation.

As can be seen in Figure 10 (a) and (b) the difference between the corrugated surfaces is evident. In Figure 10 (b) the corrugated surface is contained between the auxiliary surfaces, showing that the alignment was performed preserving the height of the corrugation, without mashing the corrugated profile of the plate. The corrugated geometry that had a deformation of around 2.43 mm at its maximum point, with respect to the lower auxiliary flat reference surface, now presents a uniform height, reducing this distance to 0.092 mm.

Digitally the mesh nodes located at the interface between the contacting bodies may interpenetrate. This phenomenon does not physically occur, and the value of this crossing between the bodies should be kept as small as possible, but keeping the penetration close to zero makes convergence difficult, even more so for complex problems. Thus, the interaction of the contact points between the auxiliary planar surfaces and the corrugated plate surface resulted in a maximum penetration of 0.22 mm, see Figure 11, thus resulting in a variation of $\pm 7.5\%$ on the standard plate height of 3.2 mm.



Figure 11. Penetration points between the auxiliary plate surfaces and the corrugated plate.

The greatest penetration between the surfaces is located at the edge of one of the corrugated plate ports. However, this region is excluded when the inlet and outlet pipes are inserted into two of the ports, while the other two remaining ports are eliminated from the channel geometry by the gasket. Thus, the region that influences the formation of the fluid channels has a penetration of less than 0.17 mm.

The channels that represent the fluid volume between the plates were obtained with the overlapping of two H plates. However, it is necessary to place a spacing between the plates to remove the fluid volume, avoiding the formation of holes in the contact points, the value of this distance was approximately 0.22 mm. This spacing is associated with the variation in height of the H-plate geometry used to assemble the channels. The fluctuation in the height of the corrugations comes from some processes such as: the scanning of the plate, due to the characteristic resolution of the scanner; the mesh enlargement to describe the corrugated surface to perform the mechanical simulation, a process that can change the location of some points in the mesh; the penetration between the contact surfaces coming from the alignment of the

corrugated surface; and the refining of the point cloud applied to transform the point cloud into a surface, procedure that can also change the location of some points in the mesh.

The three-dimensional computational domain, which describes the fluid flow through the channels formed by the corrugated plates, was obtained from the superposition of two aligned H plates. Figure 12 shows the geometry in a front (1) and back (2) view, allowing the shape of the channel formed to be visualized.

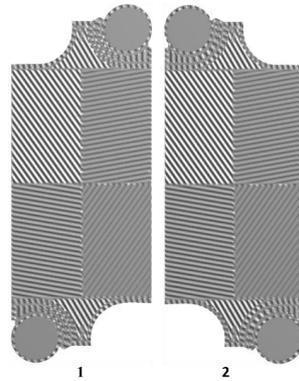


Figure 12. Computational domain representing the fluid volume between two corrugated plates. Front view (1) and back view (2).

4. CONCLUSIONS

In this study, a methodology was presented to obtain the CAD and reduce the deformations in the plate geometry of a GPHE. The plates of some heat exchangers have large dimensions and a small thickness, a combination that allows the handling, transport, and storage of the plates to promote geometric deformations. Although the GPHE plate was attached to a wooden plate, an effort was made to reduce the warping of the corrugated plate, residual deformation was captured in the scanning process. The 3D Scanner used to scan the plate has a good resolution (0.030 mm), setting a very low error source. However, the scanned H-plate showed a deformation of 2.43 mm at its maximum point, with respect to a flat surface positioned at its minimum point. CAD alignment was then performed applying FEM, and the methodology showed a satisfactory result, reducing the deformation at the maximum point to 0.092 mm, respecting the amplitude of the original geometry of the H-plate that was preserved. However, a virtual penetration of 0.22 mm at its maximum point was observed, resulting from the interaction between the corrugated plate and the auxiliary surfaces, promoting a variation of $\pm 7.5\%$ in the standard plate height of 3.2 mm. In addition, the point cloud and mesh treatments, performed during the process of obtaining the aligned CAD, can change the positioning of the points. However, the final CAD obtained from plate H presented an adequate alignment, being possible to perform the assembly of the plates and remove the volume occupied by the fluid for future studies.

5. ACKNOWLEDGEMENTS

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