Proceedings of the 9th World Congress on Mechanical, Chemical, and Material Engineering (MCM'23)
Brunel University, London, United Kingdom –August 06-08, 2023
Paper No. HTFF 170
DOI: 10.11159/htff23.170

Development and Validation of a Tubesheet Geometry Generator Tool for Efficient Heat Exchanger Design

Isaak Dassa[1], Konstantinos Karamitsios[1], Dimitrios Mertzis[1]
[1]My Company Projects
Olimpiou Diamanti 20 GR 54626, Thessaloniki, Greece
dmair@tee.gr; kk@mycompany.com.gr; jimmer@auth.gr

Abstract **-** Heat exchangers are critical components in many industrial applications, and tubesheets play a vital role in their efficient design and operation. Tubesheets are designed to support the heat exchanger tubes and withstand thermal stress due to temperature differences between hot and cold fluids. However, the design of tubesheets poses several challenges, such as determining the number and spacing of tubes, calculating tubeless flow area, and selecting the tube-to-tubesheet joint. Various design codes and standards have been developed to guide the design, fabrication, and inspection of heat exchangers and pressure vessels. To address the challenges associated with tubesheet design, a Tubesheet Geometry Generator program has been developed. This cloud-based program is written in object-oriented PHP and includes functions for calculating various properties of the tubesheet, such as the minimum required thickness based on applied loads and stresses. The program considers loads from differential pressure, weight, and thermal expansion and contraction of tubes, among others. The tubesheet generator tool efficiently and accurately generates tube layouts for heat exchangers, resulting in time and cost savings. The integration of the tubesheet geometry generator program into pressure vessel design software can streamline the tubesheet design process and improve efficiency, accuracy, and safety. The tool has the potential to benefit mechanical engineers, heat exchanger manufacturers, and other professionals involved in pressure vessel design and operation. The tool's automation and use of specialized tools for processing the output significantly improve the time efficiency of engineering calculations and help reduce errors, ensuring high-quality calculations. The tool's accuracy has been verified by comparing its results with layouts created by other verified software tools. The average relative errors for the three case studies are less than 0.7%, indicating practically identical results.

Keywords**:** heat exchanger, shell and tube, tubesheet, tube geometry, software tool, pressure vessel design

1. Introduction

Heat exchangers are crucial components in a wide range of industrial applications such as power generation, chemical processing, refrigeration, and many others. One of the most important components of a heat exchanger is the tubesheet, which serves as a support structure for the heat exchanger tubes.

Tubesheets are typically designed using analytical calculations or finite element analysis (FEA) [1][2]. However, the design of tubesheets is challenging due to various factors. Several studies have been published in the area of tubesheet analysis [3], [4] and even more focused on tube-to-tubesheet joints [5]. The pressure exerting across the tubesheet can cause high stresses, leading to failure. Therefore, the calculation of the tubeless flow area is essential in determining the strength of the tubesheet, but less tubes, mean less heat transfer area. Another challenge in tubesheet design is the determination of the number and spacing of the tubes. Tubesheets with a large number of tubes require careful consideration of the spacing between the tubes to ensure that there is sufficient space for the fluid to flow. This can be a difficult balancing act, as increasing the number of tubes will increase the heat transfer rate, but also lead to increased pressure drop. So the engineering integrity issues (of tubes, tubesheets and shell components in a heat exchanger), are quite often related to thermal rating issues. Even the tube layout, leads to different mechanical design of the tubesheet but also affects the thermal rating of a heat exchanger. Kallannavar et al, [6], studies the effect of tube layout on the performance of shell & tube heat exchangers concluding at highest heat transfer rates for 30° tube layouts. But such layouts could lead to increased tubesheet thickness due to mechanical reasons.

Heat exchangers are designed in two steps. The first step involves thermal rating (sizing) of the heat exchanger. Engineers are provided certain process data and are asked to create a heat exchanger suitable for the conditions involved. The process is iterative and involves numerous repetitions of calculations until the proper sizing is reached. Typically experienced engineers are involved in such projects. This job has been made easier using software that performs the iteration procedures and processes various solutions much faster. Still, there can be many solutions; from which designer chooses the most suitable in terms of process flow, available space, materials, ease of manufacture etc.

Several techniques such as genetic algorithms [7] have been used to optimize the optimal design of heat exchangers. The optimization procedure involves the selection of the major geometric parameters such as the number of tube-passes, standard internal and external tube diameters, tube layout and pitch, type of head, fluids allocation, number of sealing strips, inlet and outlet baffle spacing, and shell side and tube-side pressure drops. In Handibag et al (2020) [8], the HTRI software was used to simulate the heat transfer process and calculate the heat transfer coefficient and pressure drop. The HTRI software was found to be an effective tool for thermal design and analysis of tube and shell heat exchangers. Beldar and Komble [9] focuses on the design of shell and tube heat exchangers in accordance with the ASME Section VIII standard. The paper describes the mechanical design of the heat exchanger, including the design of the shell, tube sheets, tubes, and other components. The importance of proper material selection and manufacturing tolerances is emphasized throughout the paper, as these factors can greatly impact the performance and safety of the heat exchanger.

The purpose of this research paper is to introduce a new tool for the design of heat exchanger tubesheets, which is part of a larger software package for pressure vessel design. The tool was developed to address some of the challenges and limitations associated with traditional tubesheet design methods, including the difficulty in accurately modeling the tube-to-tubesheet joint and the time-consuming process of manually calculating the tube pitch and size. The paper provides a detailed description of the tubesheet generator tool, including its features, functionality, and accuracy. The validation process of the tool is also discussed, which involved comparing the results generated by the tool with those obtained from the industry-standard heat exchanger design software (HTRI) for three different case studies.

2. Methodology

2.1. Tubesheet geometry generator algorithm description

The tubesheet generator program is part of a collaborative cloud platform (vClavis - http://www.vclavis.com) developed by the authors and dedicated to pressure vessel design. The platform is at beta stage and supports all the major PV design codes (ASME, EN13445, AD2000 and PD5500). Through the integration of the tubesheet generator program with the platform, the user can instantly review the effect of the tubesheet geometry on the heat exchanger components' strength. The tubesheet generator program is written in object-oriented PHP and its main computing part is a class that consists of the necessary methods to solve the case set by the user. The necessary data for the operation of the class are given in a web browser page written in HTML. The results are displayed on a web browser page and depending on the user's requirement these are numerical and/or graphical.

Initially, the number of tubes that can fit in both the vertical and horizontal axis is calculated, depending on the case requirements and on the constraints set by the user. The cross-section needs to be symmetrical, and the solution in one quadrant is usually sufficient for finding the entire distribution of the tubes on the plate. Once this distribution is fully defined, the total number of tubes, the number of tube rows, the number of tubes per pass (plate section), and the actual diameter that results from the points of the farthest tubes (Real OTL = Outer Tube Limit) are calculated. These calculations are important in the field of heat exchanger design, as they inform the final design of the plate and its performance.

Next, the necessary geometric characteristics are determined based on two heat exchanger standards (ASME BPVC and AD 2000-Merkblatt). These are the perimeter created by the folded line that connects the centres of the external tubes of the plate, the area created by that perimeter, a scaling factor for the diameter that is created if tubes are removed from the inlet (top) or outlet (bottom) of the plate and the area created by the voids that the user specifies for the inclusion of the pass partitions. The algorithm supports heat exchangers with up to 10 tube passes and 30°, 45°, 60° and 90° tube layouts. According to the technical and practical experience of the authors, the limit of 10 passes is sufficient for the vast majority of heat exchanger requirements in practice. Other parameters required to calculate tubesheet geometry, such as tube diameter, layout angle, tube pitch, pass partition spacing, and groove alignment are shell information input set by the user.

The code includes four functions that work together to calculate the number of tubes. The first function calculates the diagonal tube pitch based on the distance between two adjacent tubes in a straight direction. The second function calculates the number of tubes on each axis of the pattern based on the midpoint of the pattern and the diagonal tube pitch. The third and fourth functions calculate the number of tubes on each quarter-axis of the pattern, excluding the midpoint, based on the distance between the midpoint and the tube centerline, and the diagonal tube pitch. Additionally, the model includes functions for calculating various other properties of the tubesheet, such as tube layout and baffle spacing. These codes are implemented as separate functions within the Tubesheet Geometry Generator. The codes are designed to be modular and can be used together to generate tubesheet geometry for a variety of mechanical and electrical engineering applications.

2.2. Integration with pressure vessel design process

In the second phase and since the geometry is fully defined, under a certain engineering Pressure Vessel Code (i.e ASME VIII, EN13445, AD2000, PD5500 - TEMA), the heat exchanger integrity under pressure is examined. Hence, the required thicknesses for all pressurized components of the heat exchanger are specified. Finding the thickness of a cylindrical shell component is quite straightforward, calculated through a single equation. Finding the required thickness of the tubesheet, can be challenging however, since this involves meticulous step by step calculations and examination of multiple scenarios which inflict the tubesheet. The tube sheet calculations involve determining the minimum required thickness of the tube sheet based on the applied loads and stresses (bending, shearing). The loads on the tube sheet are caused by the differential pressure between the shell and tube side fluids, the weight of the tubes and the baffles, and the forces generated by the tube expansion and contraction due to temperature changes.

The required steps and scenarios to determine the required plate thickness consist of determining the maximum differential pressure between the shell and tube side fluids, the maximum tube side pressure, calculating the load due to the weight of the tubes and baffles, the thermal load due to the tube expansion and contraction, the stress in the tube sheet due to the applied loads and finally comparing the calculated stress to the allowable stress for the tube sheet material to determine the required thickness. Important geometry data which are directly obtained from tubesheet layout and are also requested by the PV Codes in order to specify the tubesheet thickness are a) the tube pitch and tube layout angle, b) the Outer Tube Limit (OTL – D_o) and c) tube diameter and thickness.

However, for the calculation of shear and bending stresses, additional geometry input data are needed by the PV Codes. Usually these are obtained by engineers through manual processing of the tube layout geometry. Since pressure and geometry data are given, then selecting a thickness leads to stresses, which are then deemed acceptable or not, based on material allowable stress at design temperatures. In ASME / PD5500 - TEMA / EN13445 PV Codes, the equations for tubesheet shear stress calculation are similar:

$$\tau = \left(\frac{1}{4\mu}\right)\left(\frac{1}{h}\left\{\frac{4A_p}{C_p}\right\}\right)|P_s - P_t| \quad (1)$$

Where, τ: Shear stress (Pa), μ: Tube pitch (mm), h: Tubesheet thickness (mm), P_s: Pressure on shell side (Pa), P_t: Fluid pressure on tube side (Pa).

Regarding the untubed lane area A_L, there is a slight difference in its definition among pressure vessel codes. In ASME Code, this area is the result of the OTL length multiplied by the tube to tube distance. As stated in PD5500 - TEMA & EN13445 the untubed lane area is set from the outer tube centre r_o and not the outer edge distance. This study adopts the concept of ASME for untubed lane area calculations, since, according to the authors, ASME provides the most sophisticated formulas for tubesheet evaluation. So, the untubed lane area is considered based on OTL and not the outer tube centre. It should be emphasized that no direct formulas are given in Codes except for shapes that merely provide guidance to engineers (for simple tube layouts).

As mentioned in the introduction section, uniformly perforated tubesheets are not common in industry. There is usually an unperforated rim, which is a non-drilled area outside the main tube bundle. This area is often created by thermal engineers when designing heat exchangers, to provide sufficient space for nozzle flow, otherwise excessive fluid velocities in shell side would occur. Although the PV Codes provide some guidance for the conception of the un-tubed lane areas, designers need to be aware of PV Code limitations. Calculating the untubed lane areas by using the product of OTL and lane distance, it is clear that, the vertical lane would intersect with the tubesheet unperforated rim. In fact, the vertical lane within the perforated tubesheet area, is smaller than what the PV Code would account for. It is important to obtain a smaller un-tubed lane area, taking into account the existence of the unperforated rim, since smaller A_L leads to higher tubesheet stresses (i.e. according to the stress formulas tubesheet equivalent pitch p* changes).

Hence, the current model provides an area estimation which incorporates the guidelines EN13445/PD5500 and ASME methods, and calculates the untubed lane area A_L taking into consideration that there may be unperforated tube rims thus finding the untubed lane area within the perforated area, excluding unperforated rims.

2.3. Geometry generator verification process

The verification process of the tubesheet generator tool involves comparing the output generated by our tool with the output of the HTRI (Heat Transfer Research, Inc.) software, which is the most widely accepted software for heat exchanger design. To ensure accuracy and reliability, we have followed the general rules applied in software development science for tool verification. We have designed a test suite that includes a range of test cases covering various scenarios, such as different tube pitches, tube diameters, baffle types, and shell-side fluids. For each test case, we have compared the output generated by our tool with the output of the HTRI software, and any discrepancies were investigated and resolved. The verification process has been carried out for both ASME and AD2000 pressure vessel codes. The comparison of various tubesheets in order to evaluate the results of the proposed tubesheet generator in respect to the PV Code requested values and in respect to classic thermal software output is expressed through three different examples-case studies. The short description of the three examples is listed in Table 1.

Table 1: Summary of heat exchanger cases studied for verification

Example #	Case study-application	Tube layout	Main tube data (passes, angle)
A	BEU heat exchanger	Pie	4 / 30°
B	AES heat exchanger	Mixed	6 / 60°
C	BEM heat exchanger	Mixed	10 / 90°

3. Results and discussion

The tubesheet generator model described in the methodology section increases time efficiency and accuracy of results. The accuracy of the tube layout generated by the tool is evaluated by comparing it with the layout created by verified software tools such as HTRI. Geometrical properties such as the deviation in the number and position of tubes in the tubesheet and the various geometrical properties required by the PV Codes are analysed. The geometries resulting from the thermal calculation are exported as "**.dxf*" format files and processed in Autocad. The MASSPROP [10] and REGION [11] commands are used to identify closed areas and extract their geometrical properties. The results are compared with the tubesheet generator model outputs. A comparison is presented in Table 2.

The table contains the basic geometrical parameters used by the PV Codes to calculate the mechanical properties of the design. The outer tube perimeter, the area by outer tubes, the un-tubed area, the radius l, and the total tubed area are presented for each case study using the model and verification methods. In Case A, the model and verification values of the outer tube perimeter and radius l are indistinguishable, suggesting the absence of dissimilarities in the calculations. The area by outer tubes and un-tubed area values show a small discrepancy, leading to a relative error (RE) of 1.26E-07 and -5.79E-04, respectively. Additionally, the total tubed area displays a slight difference between the model and verification values, with an RE of 4.00E-06. Similarly, for Case B, the model and verification values of the outer tube perimeter and radius l are identical. There is a minor difference in the area by outer tubes and un-tubed area values, leading to an RE of 3.82E-07 and -1.20E-03, respectively. Additionally, the total tubed area indicates a small difference between the model and verification values, with an RE of 3.56E-06. Finally, in Case C, the model and verification values of the outer tube perimeter are the same. Nevertheless, the untubed area values shows the most considerable discrepancy, however still negligible, with an RE of -6.70E-03. There is no difference between the model and verification values for the area by outer tubes and radius l. The total tubed area reveals a minor difference between the model and verification values, with an RE of 6.05E-06.

Table 2: Summary of case study tubesheet geometry results for ASME, PD550, EN13445 (I-III) and AD2000 (IV-V) Codes.

Example	Method	Outer tubes perimeter (I)	Area by outer tubes (II)	Un-tubed area (III)	Radius l (IV)	Total tubed area (V)
		[mm]	[mm2]	[mm2]	[mm]	[mm2]
A	Model	1234.15	95220.213	31715.095	161.53	72588.130
	Verification	1234.15	95220.225	31696.720	161.53	72588.420
	RE [-]	0	1.26E-07	-5.79E-04	0	4.00E-06
B	Model	1209.55	94172.602	35529.776	158.155	69400.524
	Verification	1209.55	94172.638	35487.155	158.155	69400.771
	RE [-]	0	3.82E-07	-1.20E-03	0	3.56E-06
C	Model	1320.60	87755.508	57578.197	131.38	46649.448
	Verification	1320.60	87755.508	57192.440	131.38	46649.730
	RE [-]	0	0	-6.70E-03	0	6.05E-06
Average RE [-]		0	1.69E-07	-0.00283	0	4.54E-06

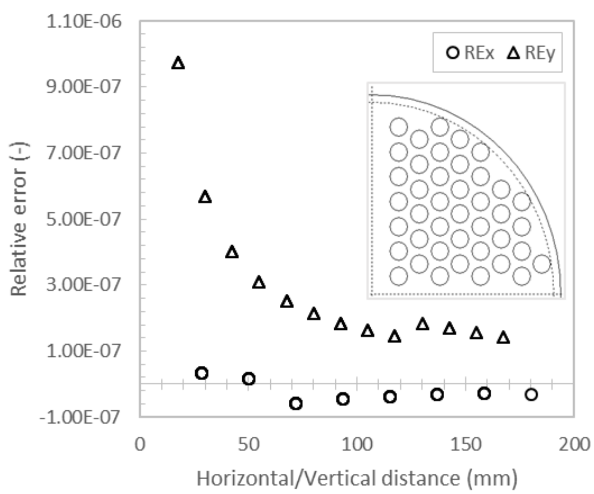

Fig. 1: Relative error distribution along the horizontal and vertical axes for the top right quadrant (Example A)

The average relative errors for the three case studies are presented at the bottom row of Table 2. The outer tube perimeter and radius l show no difference between the model and verification values. The area by outer tubes shows a small discrepancy with an average RE of 1.69E-07, and the untubed area shows the highest discrepancy with an average RE of -0.00283. The total tubed area shows a small difference between the model and verification values with an average RE of 4.54E-06. On average the highest error is in the calculation of the untubed area. The model systematically overestimates the tubeless area the HEX design is on the safe side as higher tubeless area leads to higher stresses. All differences are less than 0.7% practically leading to identical results. Figure 1 illustrates the tube centre coordinates RE distribution along the horizontal and vertical axis for positive X and Y coordinates (top right quadrant) for example A. The points represent the RE of tube centre coordinates. The RE of the X coordinates is on average a range of magnitude smaller compared to the Y coordinates RE. Moreover, the Y-coordinate RE follows a power distribution maximizing near the centre line and minimizing near the

OTL. This distribution is a result of the algorithm as the tube distribution is anchored by the OTL which is set as an input and is calculated towards the centre axis.

Time efficiency is the time taken by the tubesheet generator tool to create a tubesheet up to the final tubesheet calculations. It can be measured and compared with the time taken by manual methods or other available software tools. type of comparison is expressed qualitatively through comparison of the design processes followed in each case. The steps and an estimation for the required man-effort are illustrated in the graphic in Figure 2.

The proposed method for calculating the properties of a pressure vessel using the vClavis platform and the tubesheet geometry generator model is likely to be more time-efficient than the classical approach of manually processing CAD files. This is due to the proposed method's focus on automation and the use of specialized tools for processing the output. In contrast, the classical approach involves manual CAD file processing and is therefore likely to be more time-consuming and require more man-effort. In general, the integration of automation tools and specialized software platforms has significantly improved the time efficiency of engineering calculations. By leveraging these tools, engineers can quickly and accurately analyze complex systems, freeing up more time to focus on other critical areas of the design process. In addition to reducing the amount of manual work required, the use of automation and integrated software can help to reduce errors, ensuring that calculations are of high quality.

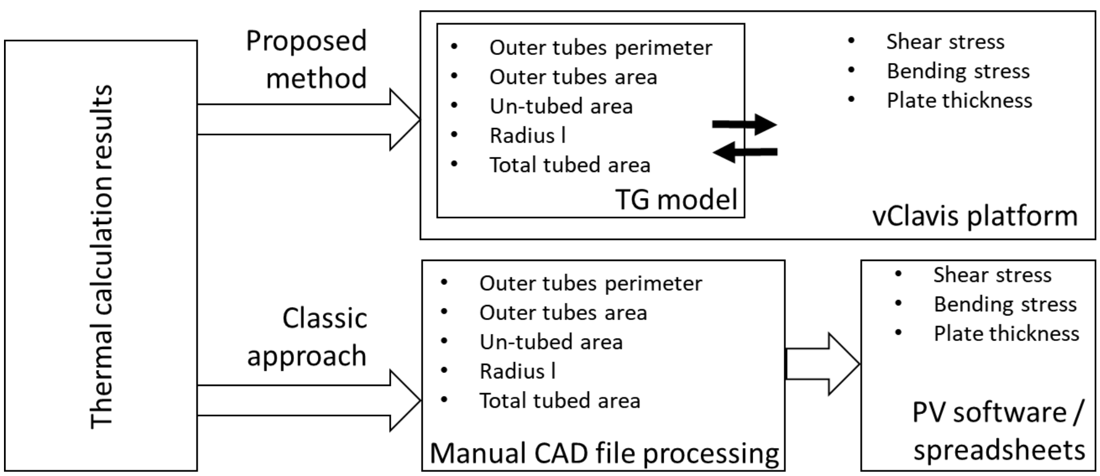

Fig. 2: Process flow comparison of the proposed model integration in PV software compared to the current status quo in the industry

4. Conclusion

The developed tubesheet generator tool can efficiently generate the tube layout for heat exchangers, resulting in time and cost savings. The verification process showed that the tool is accurate, with small discrepancies between the model and verification values. The comparison with HTRI software showed that the tool is competitive and efficient, it can handle complex configurations, including different shell and tube diameters, thicknesses, pitch arrangements and up to ten tube passes. Even if the accuracy is verified with the most wide-approved tools (HTRI, Autocad), the major improvement in the heat exchanger calculation process is the tool integration with the cloud platform and the instant review of the geometry effect on the stresses on the plate and the required thickness thus minimizing the design time. Summarizing, the tubesheet generation model will produce practically any type of tubesheet, allowing for a complete generation of non-uniformly perforated tubesheets, identical to tubesheet layouts generated by thermal software. At the same time, the model calculates important geometry data to be used in engineering Codes, taking into account the actual geometries used. The integration of the tubesheet generator tool into the pressure vessel design software streamlines the tubesheet design process, allowing for faster and more accurate calculations. Overall, this research paper aims to contribute to the field of heat exchanger design by presenting a new tool that can improve the efficiency, accuracy, and safety of tubesheet design. The tool has the potential to benefit mechanical engineers, heat exchanger manufacturers, and other professionals involved in pressure vessel design and operation.

Acknowledgements

The authors would like to thank Mr. Dimitrios Bermperis PhD cand., for his invaluable contribution in the tubesheet geometry generator tool development.

This research has been co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T2EDK-04885).

European Union
European Regional
Development Fund

EPAnEK 2014-2020
OPERATIONAL PROGRAMME
COMPETITIVENESS
ENTREPRENEURSHIP
INNOVATION

ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη
Partnership
Agreement
2014 - 2020

References

[1] M. Ando, S. Hasebe, S. Kobayashi, N. Kasahara, A. Toyoshi, T. Ohmae, Y. Enuma, “Thermal transient test and strength evaluation of a tubesheet structure made of Mod.9Cr–1Mo steel. Part II: Creep-fatigue strength evaluation,” Nucl. Eng. Des., vol. 275, pp. 422–432, 2014.

[2] J. Mao, D. Tang, S. Bao, L. Luo, and Z. Gao, “High temperature strength and multiaxial fatigue life assessment of a tubesheet structure,” Eng. Fail. Anal., vol. 68, pp. 10–21, 2016.

[3] G.-D. Zhu, C.-F. Qian, and Z. Fang, “An analytical theory for the strength solution of tubesheets in floating-head heat exchangers with back devices,” Int. J. Pressure Vessels Piping, vol. 175, no. 103936, p. 103936, 2019.

[4] M. Tasavori, M. Zehsaz, and F. V. Tahami, “Ratcheting assessment in the tubesheets of heat exchangers using the nonlinear isotropic/kinematic hardening model,” Int. J. Pressure Vessels Piping, vol. 183, no. 104103, p. 104103, 2020.

[5] D. T. Thekkuden, A.-H. I. Mourad, and A.-H. Bouzid, “Failures and leak inspection techniques of tube-to-tubesheet joints: A review,” Eng. Fail. Anal., vol. 130, no. 105798, p. 105798, 2021.

[6] S. Kallannavar, S. Mashyal, and M. Rajangale, “Effect of tube layout on the performance of shell and tube heat exchangers,” Mater. Today, vol. 27, pp. 263–267, 2020.

[7] J. M. Ponce-Ortega, M. Serna-González, and A. Jiménez-Gutiérrez, “Use of genetic algorithms for the optimal design of shell-and-tube heat exchangers,” Appl. Therm. Eng., vol. 29, no. 2–3, pp. 203–209, 2009.

[8] R. Handibag, U. Potdar, and A. Jadhav, “Thermal Design of Tube and Shell Heat Exchanger and Verification by HTRI Software,” Int. J. Eng. Res. Technol. (Ahmedabad), vol. 9, no. 12, 2021.

[9] R. D. Beldar and S. Komble, “Mechanical design of shell and tube type heat exchanger as per ASME Section VIII Div.1 and TEMA codes for two tubes,” International Journal of Engineering, 2018.

[10] “Help,” Autodesk.com. [Online]. Available: https://help.autodesk.com/view/ACD/2023/ENU/?guid=GUID-CAA51229-293E-4A0C-BFF3-93226252CF13. [Accessed: 06-Apr-2023].

[11] “Help,” Autodesk.com. [Online]. Available: https://help.autodesk.com/view/ACD/2022/ENU/?guid=GUID-ADD055CD-D351-424C-91F0-B8E5526B106C. [Accessed: 06-Apr-2023].