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Design and Analysis of a Heat Exchanger Prototype using the Design for Manufacturing and Assembly (DFMA) Method with ANSYS Thermal Simulation

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ABSTRACT

The design of small-scale heat exchangers requires an approach that considers not only thermal performance but also manufacturability and low production costs. Common challenges include component complexity and high manufacturing costs in conventional designs. This study aims to design and analyze a functional, easily manufacturable, and economical heat exchanger prototype using the Design for Manufacturing and Assembly (DFMA) approach. The methods employed include conceptual design, assembly feasibility analysis, and heat transfer simulation using ANSYS to evaluate temperature distribution and heat transfer efficiency. The prototype consists of a PVC pipe as the casing, a spiral copper coil as the heat transfer medium, a water pump as a closed-loop circulation system, and a pan as the reservoir. The design results show that the prototype consists of 12 components with an estimated production cost of Rp319,000 and an assembly time of approximately 1–2 weeks using simple tools.

1. Introduction

Heat exchangers are a key element in the development of sustainable energy technology. A heat exchanger is a device that enables the transfer of thermal energy between two fluids without direct mixing between them. These devices are widely used in a variety of applications, ranging from vehicle engine cooling systems and water heaters to renewable energy power plants. The operation of a heat exchanger is based on the principle of heat transfer between two different fluids. Heat exchange occurs through the partition wall separating the two fluids [1,2].

Heat transfer can occur through conduction, convection, or radiation. In a heat exchanger, heat transfer typically occurs through conduction and convection. Conduction is the direct transfer of heat between two adjacent objects, while convection involves the transfer of heat through fluid flow. Heat exchangers are widely used components in various industrial sectors, such as power generation,

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cooling systems, chemical processes, and manufacturing. However, these heat exchangers present several challenges, one of which is their relatively high fabrication cost [3]. Material and manufacturing process factors are also complex because they involve pipe forming, welding, assembly, and leak testing. This complexity leads to longer production times and can result in higher production costs [3,4].

The heat exchanger design process takes into account not only heat transfer performance but also manufacturability and assembly considerations. Overly complex designs increase production costs, extend lead times, and complicate the assembly process. To address these issues, the Design for Manufacturing and Assembly (DFMA) approach is used as a systematic design framework [4]. By applying DFMA principles, component structures can be simplified to minimize material usage and optimize overall operational efficiency.

DFMA is a product development methodology that integrates Design for Manufacturing (DFM) and Design for Assembly (DFA) to simplify product structures, reduce production costs, and incorporate manufacturing considerations from the earliest stages of design [5,6]. The implementation of DFMA has been shown to significantly reduce the number of components while shortening assembly time.

In addition to manufacturing considerations, thermal performance analysis is also necessary to ensure that the resulting design functions properly. In this study, simulations were performed using Fusion 360 and ANSYS software to analyze the temperature distribution and heat transfer characteristics of the designed heat exchanger prototype. The simulations were conducted to evaluate the effectiveness of the spiral copper coil as a heat transfer medium. This study developed a laboratory-scale heat exchanger prototype by applying DFMA principles, starting from material selection and component reduction strategies. By combining the DFMA approach with ANSYS simulations, the goal is to achieve a heat exchanger design that is not only thermally efficient but also easy to manufacture and assemble, with low production costs [7].

2. Methodology

2.1 Planning Idea

This study began with the Planning Idea phase, which served as the foundation for the research. At this stage, the primary problem identified was the high fabrication cost of heat exchangers due to the complexity of the manufacturing process, which involves pipe forming, welding, assembly, and leak testing. Based on this problem identification, a solution was formulated in the form of applying a DFMA approach to simplify the heat exchanger design to make it more cost- and time-efficient in production.

2.1 DFMA (Design for Manufacture and Assembly)

Once the concept has been developed, the process moves on to the DFMA (Design for Manufacture and Assembly) phase. At this stage, the heat exchanger is designed with a focus on ease of manufacturing and assembly. This process involves selecting the appropriate materials, strategies to reduce the number of components, and simplifying the product’s structure. In this study, a spiral copper coil was chosen as the heat transfer medium because it offers good thermal conductivity and is easy to fabricate using simple workshop tools [7,8].

2.3 Simulation using Ansys

The design formulated during the DFMA phase was then modeled using Fusion 360 software. After modeling, the design was simulated using Ansys Fluent. The simulation was conducted to analyze temperature distribution and heat transfer characteristics. To analyze the thermal performance of the heat exchanger, calculations were performed to determine the temperature changes in the hot fluid on the coil side and the cold fluid on the shell side. These temperature changes were used to determine the magnitude of heat transfer occurring during the heat exchange process. The equations used in this simulation are as follows:

Heat transfer rate in a hot fluid (coil)

$$Q_{hot} = \dot{m}_{hot}\, c_p\, (T_{in,hot} - T_{out,hot}) \tag{1}$$

Temperature change on the coil side

$$\Delta T_{coil} = T_{in,hot} - T_{out,hot} \tag{2}$$

Meanwhile, the temperature change on the shell side

$$\Delta T_{shell} = T_{in,hot} - T_{out,hot} \tag{3}$$

Table 1
Simulation boundary conditions parameters

Parameter	Coil Inlet (Hot Fluid)	Coil Outlet	Shell Inlet (Cold Fluid)	Shell Outlet
Condition type	Velocity inlet	Pressure outlet	Velocity inlet	Pressure outlet
Temperature	350 K – 373,15 K	-	298,15 K (25°C)	-
Working fluid	Hot water	-	Cold water	-
Flow regime	Laminar (Re < 2300)	-	Laminar (Re < 2300)	-
Outlet pressure	-	0 Pa (gauge)	-	0 Pa (gauge)
Energy equation	ON	-	ON	-
Wall condition	No-slip wall	-	No-slip wall	-

2.4 Prototype Fabrication

After the design was validated through simulation, the process proceeded to the fabrication stage of a laboratory-scale heat exchanger prototype. At this stage, the designed components were physically realized using materials specified during the DFMA phase. The fabrication process involved simple tools and techniques such as cutting, coil forming, drilling, and component assembly. After all components are assembled, a visual inspection is performed to ensure there are no leaks and that the system functions properly. This fabricated prototype is then used to represent the designed heat exchanger.

2.5 Report Writing

The final stage of the research is the writing of the report as documentation of the entire process that has been carried out. The report is written systematically, covering the background, research methodology, results, and discussion. The methodology section includes concept planning, DFMA implementation, the design process, ANSYS Fluent simulations, and prototype fabrication. The simulation results and fabrication process are described to demonstrate the performance of the designed heat exchanger. The report is also supplemented with design drawings, a research flowchart, and other supporting data. The writing of this report serves as a form of scientific accountability for the research that has been conducted.

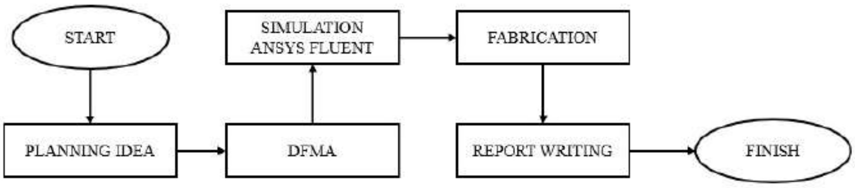


Fig 1. Workflow for heat exchanger prototyping

3. Results

3.1 Design Drawing

The heat exchanger is designed with a shell-and-coil configuration, with main frame dimensions of approximately 1705.94 mm (length) × 1246.96 mm (height). The system consists of several main components, such as a reservoir tank, a heater, hot and cold fluid pumps, and a coil pipe serving as the heat transfer medium. The coil pipes have a diameter of 15 mm and a total length of approximately 795 mm, serving as the flow path for the cold fluid inside the shell. The dimensions of the coil affect the heat transfer surface area generated during the process.

The fluid used in this system is water with a density of 1000 kg/m³, serving as both the hot and cold fluids. The hot fluid is pumped from the reservoir using a hot fluid pump into the shell with the assistance of a heater to maintain a stable temperature. Meanwhile, the cold fluid is circulated through the coil tube using a cold fluid pump with an average flow rate of approximately 0.018 m³. The temperature difference between the two fluids is the primary factor in the heat transfer process occurring within the unit.

Based on its operating principle, heat transfer occurs via convection in each fluid and via conduction through the coil pipe walls. System efficiency is significantly influenced by the coil's surface area, fluid flow rate, and pressure loss due to friction within the pipes. The circular coil geometry causes the flow to change direction, thereby increasing turbulence and improving the heat transfer process. Overall, this heat exchanger design is quite effective at improving heat transfer performance by utilizing the dimensions and characteristics of the fluids used [9].

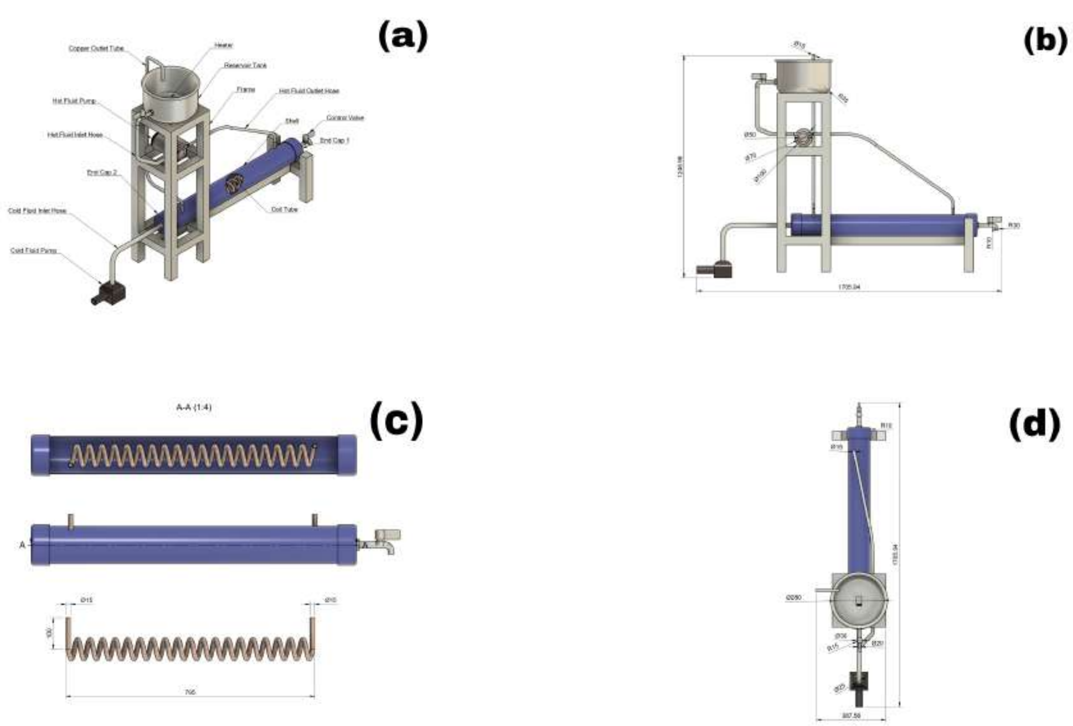


Fig. 2. Dimensions and configuration of prototype heat exchanger using DFMA : (a) front view, (b) side view, (c) shell, (d) top view

3.1 Simulation Ansys

In fig 3. (a), The simulation results the static pressure distribution in a spiral-coil heat exchanger. Based on the color contours, the highest pressure is at the hot fluid inlet and decreases gradually toward the outlet. This pressure drop occurs due to friction between the fluid and the pipe wall, as well as continuous changes in flow direction within the spiral geometry. This phenomenon is consistent with the theory of fluid flow in pipes, which states that the longer the path and the more complex the flow geometry, the greater the pressure loss that occurs [10].

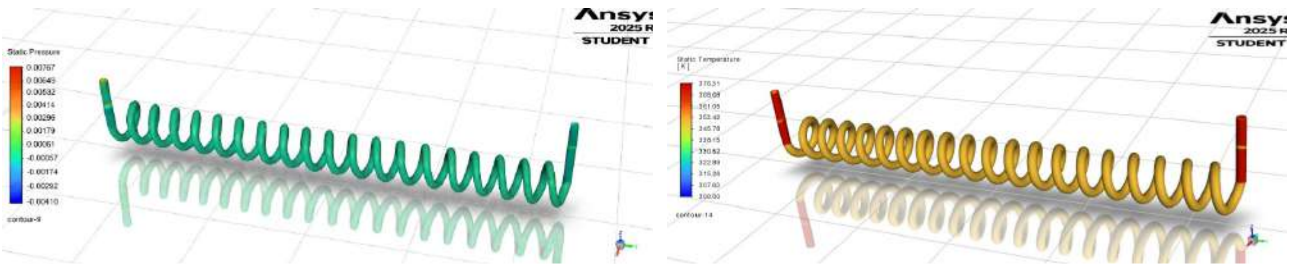
The generally smooth pressure distribution, which shows no extreme fluctuations in the simulation results, indicates that the fluid flow within the coil is relatively stable and does not exhibit significant turbulence. This supports the application of the Design for Manufacturing and Assembly (DFMA) concept, where a simple design not only facilitates the manufacturing process but also results in more controlled flow characteristics. This stable flow is crucial for enhancing heat transfer efficiency, as convection mechanisms within the fluid are strongly influenced by velocity and pressure distributions [11]. The relationship between pressure drop and thermal performance can be analyzed using the heat transfer rate equation:

$$Q = \dot{m}\, c_p\, (T_{in} - T_{out}) \quad (4)$$

Figure 3. (b), shows the results of a simulation of the temperature distribution in a spiral copper coil geometry when hot fluid flows through it, prior to being combined with the shell component and cold fluid. The simulation shows that the temperature of the hot fluid inside the coil ranges from 300 K to 376.31 K. The highest temperature is found at the coil inlet and slightly in the initial segment of the first coil turn, which is the entry point of the hot fluid before heat transfer occurs. These

conditions are consistent with the specified boundary conditions, namely an inlet temperature of 376.31 K [1,11].

Along the length of the spiral coil, the temperature distribution shows a gradual decrease from the inlet to the outlet, visualized by a color transition from red-orange at the inlet side to golden-yellow along the coil. This gradual decrease in temperature indicates that the heat transfer process occurs continuously along the coil surface, without any sudden temperature drops in specific segments [12]. This pattern is characteristic of laminar flow within a helical coil, where the temperature profile develops thermally from the inlet to the outlet [13]. Red color is again visible at the tip of the outlet pipe, indicating that the outgoing fluid still retains some of its thermal energy. This suggests that heat transfer from the coil to the surrounding environment has not yet reached its maximum in this coil simulation, and there is still potential for improved heat transfer efficiency when the coil is integrated with the coolant in the shell [1].



(a) (b)

Fig. 3. Simulation ansys fluent : (a) Static pressure coil, (b) Temperature coil

Based on the results of the static temperature distribution simulation for the heat exchanger shell in Fig 4., a temperature range of approximately 300 K to 376 K was obtained. The temperature contour shows a color gradient from red on the inlet side to blue on the outlet side. This indicates that heat transfer occurs from the hot fluid to the fluid with a lower temperature along the flow direction. The highest temperature is observed on the left side of the shell, indicated by the red-orange color. This indicates that the hot fluid enters with a high thermal energy. As the fluid flows along the shell, the temperature gradually decreases, as shown by the color transition from red-orange to yellow, green, and finally blue on the right side. This temperature drop occurs due to heat transfer between the fluid inside the shell and the fluid in the coil pipes within it [11,14].

The relatively smooth temperature distribution, with no drastic changes, indicates that the heat transfer process is stable and uniform. The temperature gradient formed along the axial direction of the shell indicates that the dominant heat transfer mechanism occurs via convection between the shell fluid and the surface of the coil tubes, followed by conduction through the tube walls [11,15]. The inlet and outlet nozzles at the top of the shell also exhibit local temperature variations. In these areas, more pronounced color changes are visible due to the inflow of fluids at different temperatures, which causes flow mixing inside the shell. This helps increase flow turbulence and can improve heat transfer performance [14,16].

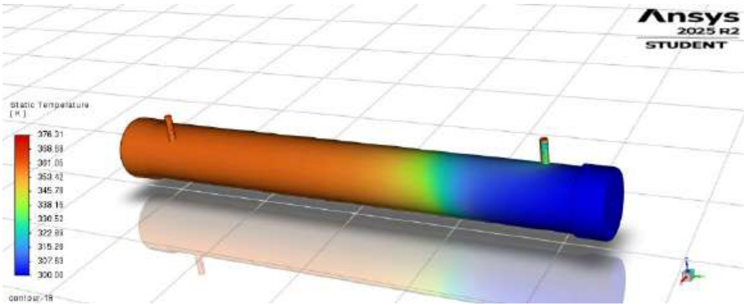


Fig. 4. Static temperature shell

3.3 DFMA Implementation and Component Analysis

The first component, the PVC pipe shell, undergoes the primary processes of drilling and chamfering, denoted by the codes D and CH. based on Table 2, Drilling is performed to create fluid inlet and outlet holes, while chamfering is used to smooth the edges of the holes to facilitate the installation of other components. The selection of these processes indicates that the PVC pipe is a fabricated component because it undergoes modification before assembly. In DFMA, selecting simple manufacturing processes such as drilling and chamfering can improve ease of assembly and reduce product design complexity.

Copper coils undergo shaping and grinding processes designed to form the copper tubing into a spiral and smooth the surface of the formed coil. The shaping process is used to form the coil in order to increase the heat transfer surface area. Grinding is performed to ensure the coil's surface is smooth, making installation into the shell easier. The terms "fabricated" and "purchased" indicate that coils can be purchased as raw materials and then modified to meet the specific design requirements of the heat exchanger [17].

The PVC pipe cap and pot components undergo a drilling process because they require additional holes for fluid pathways or coil installation. As shown in Table 2, Both components are classified as purchased parts because they are acquired in finished form and then modified as needed. This approach aligns with DFMA principles, which recommend the use of standard components to reduce manufacturing costs. The use of purchased components can also speed up the production process and reduce product development time [18].

Water faucets, water pumps, hoses, Pilox paints, PVC glue, and iron glue do not require any additional manufacturing processes because they are used directly in their finished state. These components are classified as "purchased" to simplify the assembly process and reduce fabrication time. In the DFMA concept, the use of standard components available on the market can lower production costs and improve system reliability. Additionally, purchased components simplify the maintenance process because they are easy to replace in the event of damage[19].

Frame components undergo grinding and shaping processes because the frame must be formed and refined before it can be used to support the system. The shaping process is performed to form the frame structure to fit the equipment's dimensions, while grinding is used for surface finishing after cutting or welding. The frame is classified as fabricated because it is custom-made to match the dimensions of the heat exchanger. In DFMA applications, fabricated components are typically used for major structural parts that are not available as standard components [20].

Table 2
Summary of processes for each component

No	Component Name	Main Process								Type
		T	CB	D	M	G	S	F	CH	
1	Pipe (PVC) Shell	N	N	Y	N	N	N	N	Y	F
2	Copper Coil	N	N	N	N	Y	Y	N	N	P, F
3	PVC Pipe Cap	N	N	Y	N	N	N	N	N	P
4	Water Faucet	-	-	-	-	-	-	-	-	P
5	Water Pump	-	-	-	-	-	-	-	-	P
6	Hose	-	-	-	-	-	-	-	-	P
7	Frame	N	N	N	N	Y	Y	N	N	F
8	Pot	N	N	Y	N	N	N	N	N	P
9	Pilox Colors	-	-	-	-	-	-	-	-	P
10	PVC glue	-	-	-	-	-	-	-	-	P
11	Iron glue	-	-	-	-	-	-	-	-	P

Note : T=Tapping, CB=Counterboring, D=Drilling, M=Milling, G=Grinding, S=Shaping, F=Fillet, CH=Champer, F= Fabricated, and P = Purchased

4. Conclusions

This study designed and analyzed a laboratory-scale heat exchanger prototype by combining the Design for Manufacturing and Assembly (DFMA) approach with thermal simulation using ANSYS Fluent. The background of this study stems from common challenges in the manufacture of conventional heat exchangers, namely high fabrication costs resulting from complex processes such as tube forming, welding, and leak testing. ANSYS simulation results show that the pressure distribution in the spiral coil is stable and decreases gradually from the inlet to the outlet, reflecting controlled fluid flow without significant turbulence. The temperature distribution in the coil also shows a gradual decrease from the inlet to the outlet, indicating that heat transfer occurs continuously along the coil surface. In the shell section, the temperature gradient forms uniformly from the inlet side to the outlet side, indicating that heat transfer mechanisms via convection and conduction are functioning well and stably. The application of the DFMA approach simplifies the design by maximizing the use of commercially available components and minimizing complex fabrication processes. The result is a heat exchanger that is not only thermally efficient but also easy to assemble and economical to produce, making it a relevant solution to the issues of complexity and high production costs typically associated with heat exchangers.

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