

Development of a Heat Recovery unit for Residential Applications

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Abstract

When considering the design for a heat recovery unit for residential applications, there are many possible configurations. The most fundamental design will be some form of heat exchanger that will use hot air to heat a cool fluid stream of water. The task is to design a unit for heating water flowing at 2.12 LPM by exactly 4 degrees centigrade from an initial temperature between 22.0 and 24.0. Any deviations in this temperature change must be justified. The heat exchanger used for preliminary calculations is an unfinned counter flow heat exchanger; however, different configurations will be explored throughout this report to determine the most efficient one with the smallest area of heat transfer.

The overall design of the unit has very few constraints, and any reasonable model can be considered. The only given design constraint is that the air or hot fluid must have an outlet diameter of 6 inches, and the warm air flow must exit at a velocity of 10 m/s and a temperature of 45 degrees centigrade. Some fair assumptions that were made are that the thermal properties will remain consistent, both fluid streams are fully developed, the kinetic and potential energy changes are negligible, and that no heat is lost to the surroundings. The preliminary design resulted in about 16% efficiency. For the initial calculations, the inlet and outlet diameter will be the same and any potential fouling factors will be ignored. The fouling factor, however, will be considered in later designs.

Date of Submission: 15-10-2023

Date of acceptance: 31-10-2023

I. Introduction

For this report, a heat recovery unit for residential application was used to design and analyze a heat exchanger. Devices like heat exchangers are used since they facilitate the exchange of heat between fluids having different temperatures without having to mix them, unlike mixing chambers where the fluids do mix. To analyze the heat transfer between the fluids, the overall heat transfer coefficient, U , is used, taking into account all the effects during heat transfer such as convection and conduction. Heat transferred from the hot fluid to the wall is done by convection through the wall by conduction and again by convection from the wall to the cold fluid. Thermal resistance through a tube wall can be negligible when the wall thickness of the tubes is small as it is in this case. With a quick literature search, numerous articles point out the use of a heat recovery unit when looking at history; it is unclear when it was first invented.

Nevertheless, there are patents dating from 1983 by Rolf A. S. Kruse, Karl A. L. Gustavsson, Karl A. Jansson. At first glance, it may seem obsolete, but the critical function is recovering the heat. It is essential to look back on patents to know which path to follow or solely for inspiration.

Furthermore, Heat recovery units are tremendously beneficial as they help recover most of the heat that is typically wasted and reduce heating requirements. This closed-cycle improves efficiency when compared to old methods. A heat recovery unit circulates fresh hot air in our homes; it also keeps out moisture and pollutants. Moisture and contaminants are created by things as simple as breathing and cooking. If humidity reaches excessive levels, it can cause structural damage. Our heat exchanger is a subunit of a complex architecture, but the general purpose is to heat fresh air without going stale. There are several different makes and models, but most heat recovery units will gain back 80%-85% of the heat of the

existing stream. They can be used in an independent heat recovery unit installation or a heat recovery with a furnace. The second option is when our heat exchanger comes into play, replacing the furnace.

In this project, a heat exchanger is installed in the exhaust of the heat recovery unit, where the hot exhaust air will be utilized to heat cold water. A heat exchanger is to be designed and analyzed to acquire the goal of warming the cold water 4°C. Analytical and modeling methods were applied using Fusion 360, and ANSYS. Designs were replicated in NX-10, but it was incompatible with ANSYS. The heat exchanger design was done using Fusion 360 and was imported to ANSYS to perform simulation and analyze results acquired and compare to the analytical results. This project aims to demonstrate the application of a counterflow heat exchanger using analytical calculations and CFD software to validate our design. The final model should be capable of heating water by 4 Celsius.

Theoretical Background

Heat recovery units come in different types of forms depending on what the unit needs to be used for, but they all contain a type of heat exchanger for it to be operable. When using heat recovery units for residential, it is important to be set up in the most convenient area. Heat recovery systems are used for heat spaces, ventilating spaces, heating water, and industrial scale drying.

The way these types of systems work is hot fluid passes next to cold fluid and the heat transfers on to the colder fluid hence the name heat exchanger. When putting a heat recovery unit in a home or office, heat recovery units work just like a ventilation system where it involves a type of heat exchanger that can sit on the roof, where it draws the cold air from the outside and warms it up with air that is being expelled from the inside.

It is known that a heat exchanger is the brain of a heat recovery unit. The role of heat exchangers is to cool or heat fluids in a system. When creating a heat exchanger for an application a lot of properties of the heat exchangers must be taken into consideration from the fluid being used, size of pipes, to what type of fittings and what type of material will be used for the piping as well as if it will have fins or not. When creating a heat recovery unit for a residential application having an efficient heat exchanger in the system is needed to work properly.

There are two types of heat exchangers that are mostly used in different types of systems that operate very differently based on the direction of the flow of the fluid. The two types of heat exchangers that are the most common are parallel flow and counter flow, and for the heat recovery unit it was decided that a counter-flow heat exchanger would be the best type of heat exchanger to use. The counter-flow heat exchanger works by having a stream of one of the fluids in the opposite direction of the flow of the other fluid compared to the parallel where the fluid flows in the same direction. Since counter flow heat exchangers have the hot fluid going through one side and the hot fluid through the other, it is more efficient because it minimizes the thermal stresses through the exchanger by the temperature difference being uniform between the two fluids, meanwhile the parallel flow exchanger has large temperature differences at the ends which causes large thermal stresses. When creating a heat exchanger an important property is cross flow whether it is un-finned or finned. When a heat exchanger is finned tubular both fluids are unmixed, and fins are guided in a direction transverse to the tube flow direction. When the heat exchanger is un-finned heat can be exchanged in all directions so that there's a chance that the fluid can mix.

Analytical Calculations

Properties of Air	Temp (C)	Density (kg/m ³)	Specific Heat (J/kg*K)	Thermal Conductivity (W/m*K)	Dynamic Viscosity (kg/m*s)	Prandtl Number
Air in	45	1.109	1007	0.02699	0.00001941	0.7241
Air Out	42.10895909	1.1198	1007	0.0268	0.000019272	0.7249
Air film	43.55447955	1.1144	1007	0.0269	0.000019341	0.7245
Properties of water	Temp (C)	Density (kg/m ³)	Specific Heat (J/kg*K)	Thermal Conductivity (W/m*K)	Dynamic Viscosity (kg/m*s)	Prandtl Number
Water in	23	997.4	4180.8	0.6034	0.0009354	6.488
Water out	27	996.6	4179.2	0.6102	0.0008538	5.852
Water avg	25	997	4180	0.607	0.000891	6.14

Table 1: Water and Air Properties

Calculating volume flow rate for water

$$V = (2.12 \text{ LPM}) \left(\frac{1 \text{ minute}}{60 \text{ seconds}} \right) \left(\frac{1 \text{ m}^3}{1000 \text{ L}} \right) = 0.0003533 \text{ m}^3/\text{s}$$

Calculating for mass flow rate

$$m_{\text{water}} = \rho * \text{volume flow rate} = (997 \text{ kg/m}^3)(0.0003533 \text{ m}^3/\text{s}) = 0.03522401 \text{ kg/sec}$$

$$m_{\text{air}} = \rho * \text{velocity} * A_c = (1.109 \text{ kg/m}^3)(10 \text{ m/s}) \left(\frac{\pi}{4} (0.1524 \text{ m})^2 \right) = 0.20229879 \text{ kg/s}$$

Calculating for volume flow rate of air

$$V = \frac{\rho}{\text{mass flow rate}} = \frac{1.109 \text{ kg/m}^3}{0.20229879 \text{ kg/s}} = 0.1824146925 \text{ m}^3/\text{s}$$

Heat Transfer

$$Q_{\text{water}} = \text{mass flow rate} * C_p (T_{\text{out}} - T_{\text{in}})_{\text{water}} = (0.03522401 \text{ kg/sec})(4180 \text{ J/kg} \cdot \text{K})(27^\circ \text{C} - 23^\circ \text{C}) = 588.9454472 \text{ W}$$

$$Q_{\text{air}} = \text{mass flow rate} * C_p (T_{\text{out}} - T_{\text{in}})_{\text{air}} = (0.20229879 \text{ kg/s})(1007 \text{ J/kg} \cdot \text{K})(45^\circ \text{C} - 42.10895909^\circ \text{C}) = 588.9454472 \text{ W}$$

$$C_c(\text{water}) = \text{mass flow rate} * C_p = (0.03522401 \text{ kg/sec})(4180 \text{ J/kg} \cdot \text{K}) = 147.2363618 \text{ W/K}$$

$$C_c(\text{air}) = \text{mass flow rate} * C_p = (0.20229879 \text{ kg/s})(1007 \text{ J/kg} \cdot \text{K}) = 203.7139792 \text{ W/K}$$

$$C_{\min} = C_c(\text{water}) = 147.2363618 \text{ W/K}$$

$$C_{\min}/C_{\max} = 0.7227602267$$

$$Q_{\max} = C_{\min} (T_{\text{hot, in}} - T_{\text{cold, in}}) = (147.2363618 \text{ W/K})(45^\circ \text{C} - 23^\circ \text{C}) = 3239.19996 \text{ W}$$

Effectiveness

$$\varepsilon = Q/Q_{\max} (100) = 18.1818\%$$

NTU

$$NTU = \frac{1}{C_{\min}} \ln \left(\frac{\varepsilon + 1}{\varepsilon - 1} \right) = 21.56455726$$

Reynolds Number

$$Re_{\text{water}} = \frac{4 * \text{mass flow rate}}{\pi D \mu} = 5355.94082 \text{ (Turbulent)}$$

$$Re_{\text{air}} = 87385.14038 \text{ (Turbulent)}$$

Nusselt Number

Using Table 7-1 from Heat and Mass Transfer Fundamentals and analyzing the range of Reynolds number for water, the equation used for Nusselt number is the following:

$$Nu_{\text{water}} = 0.193 Re^{0.466} Pr^{1/3} = 5355.94082$$

$$Nu_{\text{air}} = 0.023 Re^{0.8} Pr^{0.3} = 215.9769787$$

Heat transfer Coefficient

Using the Nusselt number equation to solve for h,

$$Nu_{\text{Cyl}} = \frac{hD}{k} \therefore h = \frac{Nu_{\text{Cyl}} k}{D}$$

$$h_{\text{water}} = 4601.017186 \text{ W/m}^2 \cdot \text{K}$$

$$h_{\text{air}} = 38.12192077 \text{ W/m}^2 \cdot \text{K}$$

Overall heat transfer coefficient

$$U = \frac{1}{\frac{1}{h_{\text{air}}} + \frac{1}{h_{\text{water}}}} = 37.80865557 \text{ W/m}^2 \cdot \text{K}$$

LMTD

$$\Delta T_1 = T_{hot,in} - T_{cold,out} = 18^\circ\text{C}$$

$$\Delta T_2 = T_{hot,out} - T_{cold,in} = 19.10895909^\circ\text{C}$$

$$TLM = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)} = 18.5489549$$

Surface Area

Using the equation for heat transfer to solve for the surface area

$$Q = U A_s \Delta T_{lm} \quad \therefore A_s = \frac{Q}{U \cdot \Delta T_{lm}} = 0.8397777986 \text{ m}^2$$

Modeling Set Up

The heat exchanger was designed using Fusion 360 and was later imported into ANSYS to perform the simulation. As settings were modified during the setup process, many results and errors were obtained. Multiple heat exchanger designs were attempted to achieve a temperature difference of 4 degrees celsius. The one below was the closest to achieving the 4 degrees. The different heat exchangers can be found in the appendix section of this report.



Figure1. Applying mesh to outer fluid

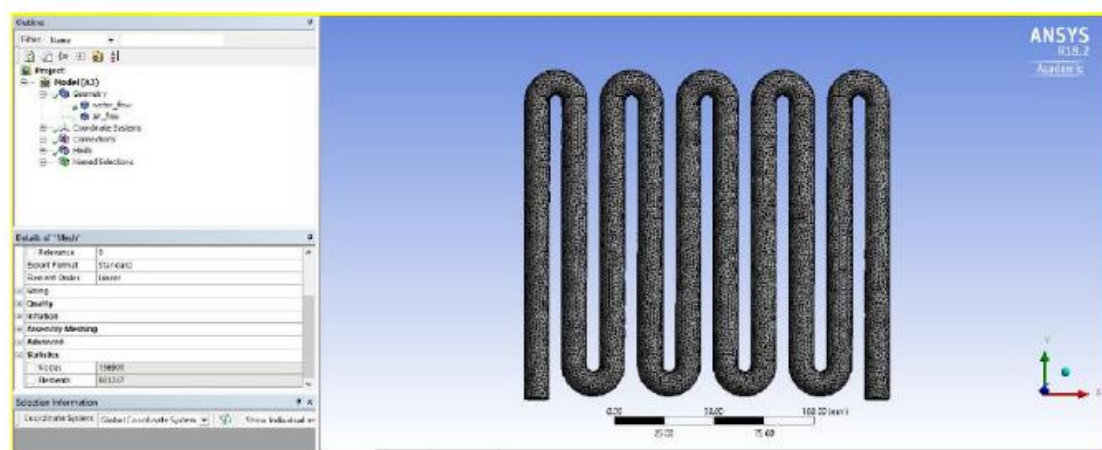


Figure 2. Applying mesh to copper pipes and inner fluid

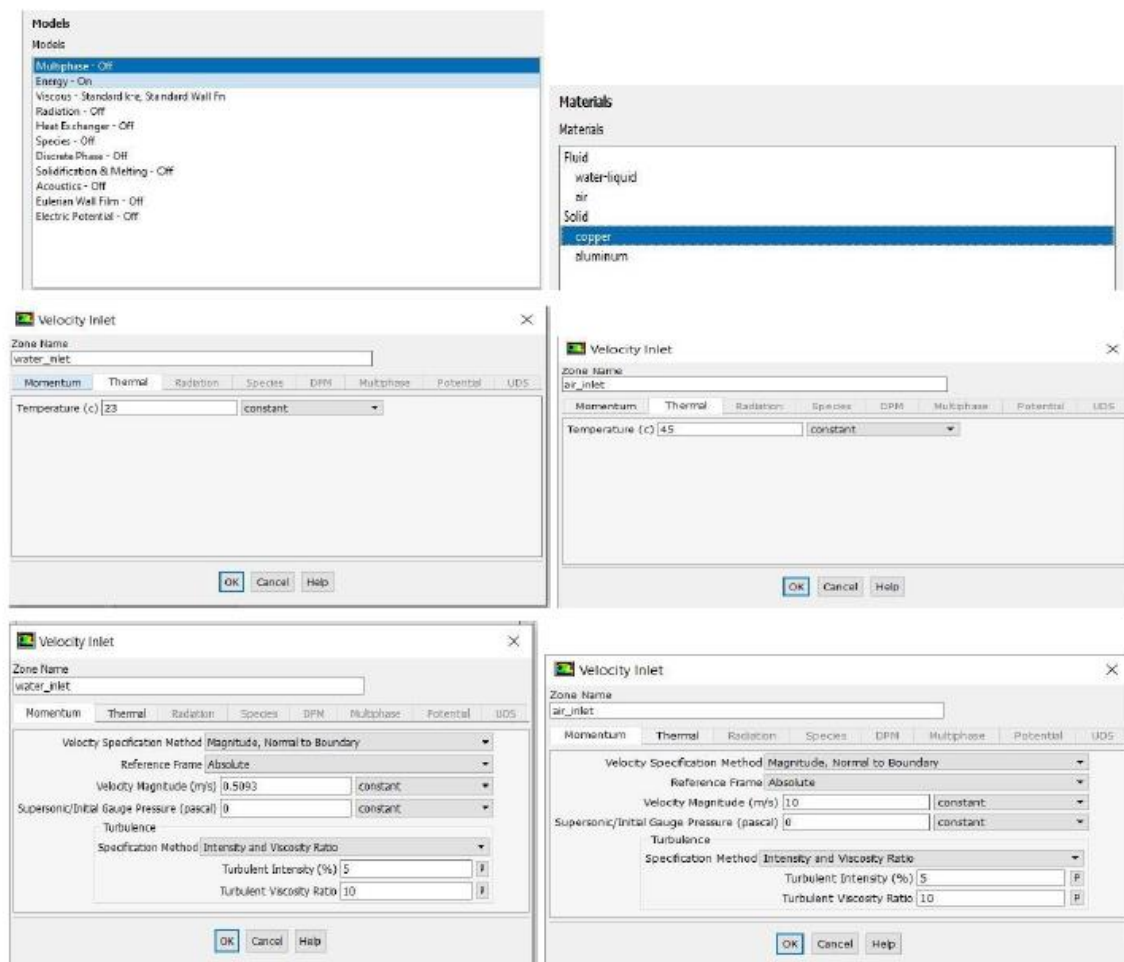


Figure 3. Simulation Conditions

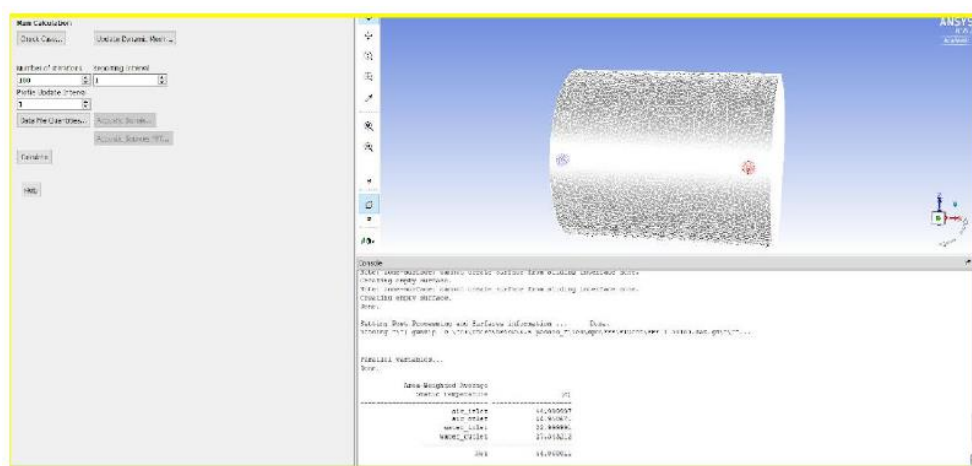


Figure 4. Running Calculations

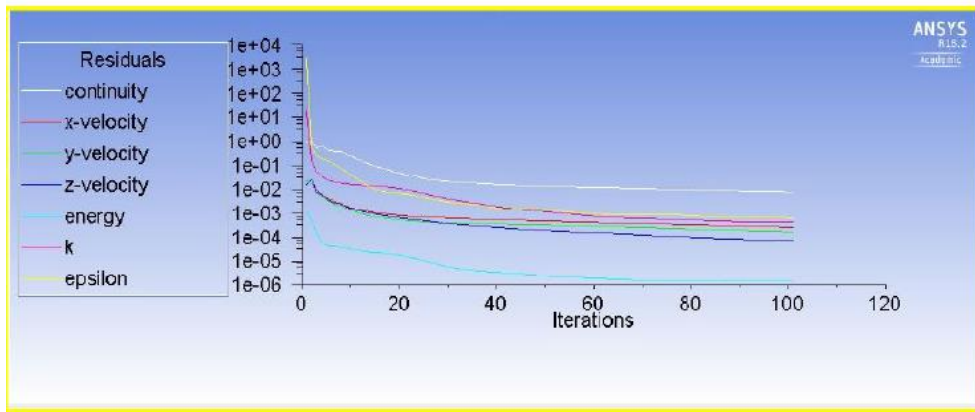


Figure 5. Iterations

II. Results

ANSYS simulation was performed on three different CAD models with three different numbers of passes (17, 11, and 10). There were technical limitations on geometry and design when simulating ANSYS, which made our initial theoretical design impossible to simulate on the software. The following results are the velocity, pressure, and temperature contours retrieved from simulating the 10 tubed CAD design, which represents the most accurate simulation when compared to our analytical calculations.

Velocity Contour:

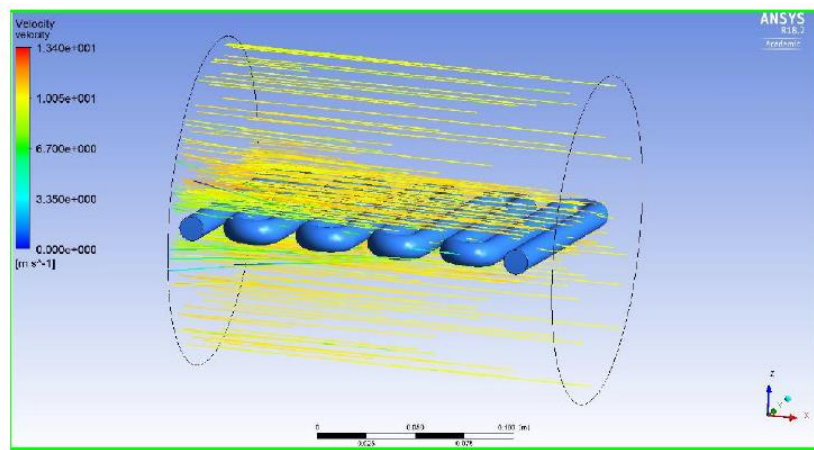


Figure 6. Velocity Contour (m/s)

Computational Fluid Dynamics (CFD) simulations were carried out to simulate the air flow through the test subject. We know that the performance of the heat exchanger is greatly affected by the distribution of air that passes through it and the features within the duct and the orientation of the heat exchanger.

Simulation shows air flowing inside the heat exchanger in a range between 0 m/s and 13.1 m/s, which agrees with the 10 m/s initial velocity declared in the set up.

Pressure Contour:

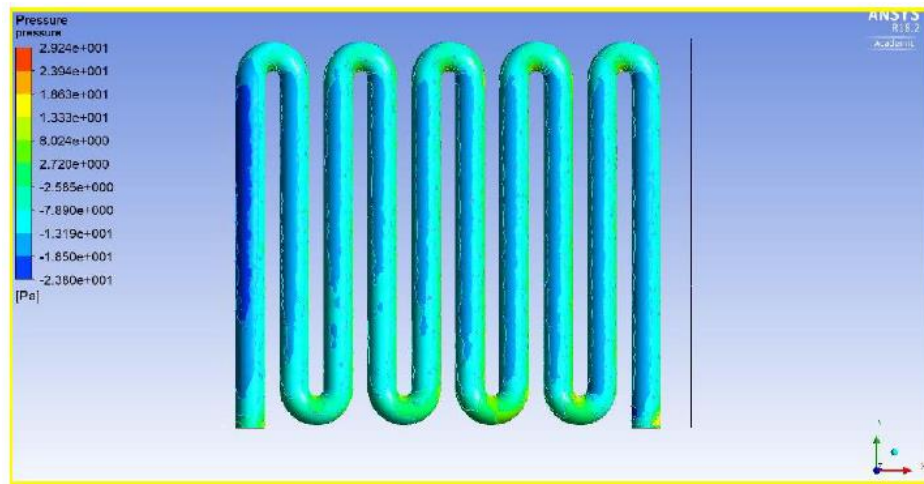


Figure 7. Pressure Contour (Pa)

The pressure contour obtained from ANSYS confirms that pressure does not remain constant in heat exchangers. This can be attributed to the fact that the fluid flowing inside the tube will create friction that leads to unavoidable pressure drop. Our simulation shows a range in pressure between -23.8 Pa and 29.2 Pa.

Temperature Contour:

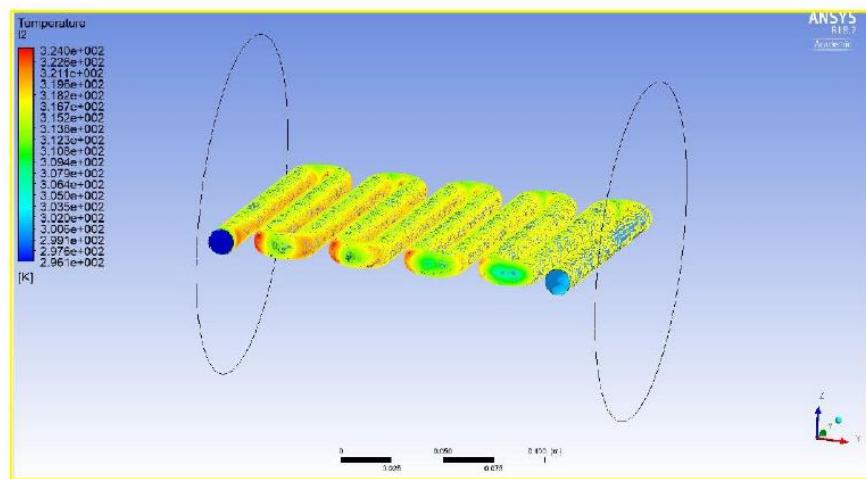


Figure 8. Temperature Contour (K)

The temperature contour shows a minimum temperature of 296.1 K located at the water inlet of the pipe. The water outlet shows a temperature in a blue gradient, which can be estimated to be between 299 K and 300 K, proving that this design successfully heats water by 4 degrees.

Costs

	# of Days	# of Hrs	Price \$/kWhr	Q Air kW	Cost per Month	Cost per Season
January	31	744	0.1111	0.588	48.6031392	Winter
February	28	672	0.1111	0.588	43.8998096	141.105888
March	31	744	0.1111	0.588	48.6031392	Spring
April	30	720	0.1111	0.588	47.035296	148.0975136
May	31	744	0.1222	0.588	53.4590784	Summer
June	30	720	0.1222	0.588	51.734592	158.6527488
July	31	744	0.1222	0.588	53.4590784	Fall
August	31	744	0.1222	0.588	53.4590784	152.2289864
September	30	720	0.1222	0.588	51.734592	
October	31	744	0.1222	0.588	53.4590784	
November	30	720	0.1111	0.588	47.035296	
December	31	744	0.1111	0.588	48.6031392	
Total in 1 Year	365	8760			601.0851168	

Figure 9. Cost of One Year

Inflation Over 10 Years	
2020	\$601
2021	\$616
2022	\$631
2023	\$647
2024	\$663
2025	\$680
2026	\$697
2027	\$714
2028	\$732
2029	\$751
2030	\$769
Total Cost	\$7,501

Figure 10. Total Life Cycle Cost

Materials and Equipment			
Item	Amount Needed	Price	Total Price
Copper Tubing 3/8 Tube Size, 1/2" OD 0.065" Wall Thickness	78"	\$33.61-6ft	\$50.41
Multipurpose Copper Sheet, .002" thick, 2" X 50 ft	1 Unit	\$42.23	\$42.23
304 Stainless Steel Pipe, 6.625 OD X .280 wall X 6.065 ID	1 Unit	\$369.06-2ft	\$369.06
Starbond Super Fast Thin CA Glue EM-02	1 Unit	\$10.50	\$10.50
		Total=	\$472.20

Figure 11. Initial Costs

The total cost was calculated using the residential electricity rates in El Paso. To get the monthly cost, the rate was multiplied with the hours of the month, and then multiplied by the rate. The average costs during the summer months are 12.22 ¢/kWhr and in the winter it is 11.11 ¢/kWhr. To calculate the costs over a span of 10 years, inflation was taken into consideration. In the final report, maintenance costs will also be included.

Safety Considerations

Heat exchangers are essential equipment for a manufacturing plant. However, heat exchanger operation and maintenance contain potential safety hazards to prevent any accidents, even death. Safety is a crucial part of the design and building to prevent accidents and also life cost of the heat exchanger. According to frankieidson.com, an injury lawyer, "Every year in the US, power tool injuries result in approximately 400,000 emergency room visits". To reduce the risk of getting hurt, the adequate personal protective equipment (PPE) should be used by every team member. Safety goggles protect the eyes from residue from pipes being cut, helmets as well to get protection from flying objects, gloves to protect hands from hot surfaces and sharp objects. It is also imperative to always be a supervisor in case of accidents and never operate a machine or heat exchanger by yourself.

III. Conclusion

In this project, a heat recovery unit was created and simulated for the purpose of heating water 4°C. Water and air entered the heat recovery unit at 23°C and 45°C respectively. All initial properties were collected at those temperatures to help calculate both mass flow rates. Once that was calculated, the heat transfer, effectiveness, and NTU were calculated. The NTU was used to determine the Reynolds and Nusselt number. The heat transfer coefficient and LMTD were then calculated to find the surface area. Multiple heat exchangers of different sizes were created to get a heat increase of 4°C. The final CAD design consisted of ten tubes and nine 180° elbows. This specific heat exchanger size was the one that yielded the closest increase to 4°C. However, the final temperature at the water outlet is 27.3°C. The reason for not getting exactly 4°C could've been caused for numerous reasons including mesh size, number of iterations, and quality.

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