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Term Project

Plate Heat Exchanger Design

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1. Abstract

Heat exchangers, as the name proposes, exchange heat between surfaces and systems with a position vector and in a time that determines its flux; the heat exchanger needs optimal control to make the ambient room temperature stay between, linearly measurable or to say, optimal controllable conditions and make the field that it is residing to be at the desired temperature levels. It can be used at a factory to produce steam; it can be used to cool down substances; it can be just the radiator we use in our houses regularly. The aim desired to be reached in this project is to design a plate heat exchanger that works within the limits of 25 psi Δp $(pressure\ drop)$. From the heat exchanger, it is also expected that to run with a mass flow rate of 13000 $\frac{kg}{hr}$ or 3.611 $\frac{kg}{s}$, and this mass should be an Acetic Acid mixture with weight percent of this fluid should be 30% Acetic acid, and the rest is water. It is also essential to be considerate of the other design specifications to be at the standards level. One should determine its port size in a range of [0 - 39] cm. Determine a minimum of 3, but not more than 700, plates to insert and determine the spacing between these plates and the thickness of these plates themselves. Moreover, the double pipe heat exchanger is designed explicitly for T_{hi} =$100^{\circ}C$, T_{ho} = $50^{\circ}C$, T_{co_max} = $35^{\circ}C$, T_{ci} = $25^{\circ}C$ to cool down the entering mixture with a specific water-flowing cooler pipe.

In essence, in the operation of solving the problem, attack the issue wanted to be at the utmost efficiency and by not using maximum or minimum, but rather by computational intelligence programmed by the designers with available data and constraints of the physical world given to the designers, for to achieve the optimal result most appropriate claims are made about the physical and mechanical properties. Essentially, claims are to form ideas on the know-how of the heat exchanger, shape, dimensions, and so. With the defined claims, appropriate calculations are based on the general procedure of plate heat exchangers[1]. It is expected to tailor-pick the dimensions for the heat exchanger. The most significant parameters we need to optimize are the pressure drop and the heat transfer rate, which are the design problem's most concerning dimensions. Calculations are conducted by Python under applied conditions of a maximum pressure drop of 25 psi to achieve the most suitable heat transfer rate. Concerned total heat transfer, heat transfer rate, and permissible pressure drop are calculated for a combination of the three iterated parameters, one selected angle, and several passes. Furthermore, with all these parameters being iterations set up, our one pass/one pass heat exchanger is designed with optimal values under given limitations. In this project, a double-pipe heat exchanger was designed according to the data are given to us and design concerns. With the calculations completed, optimal values for the vertical length(l_v), the horizontal distance (l_w), the Port Size (P), Plate Spacing (S), Number of plates (N_p), Optimum pressure drop value (Δp_p)and the thickness (t) were found.

2. Introduction

2.1 Heat Exchanger

2.1.1 What is a Heat Exchanger?

A heat exchanger, as the name suggests, is a device that transfers heat from one media to another[2]. It can be either used to remove heat or to heat a cold fluid or solid in direct contact with itself or its system[2]. One can think of swimming pools, such as jacuzzis, bubbles, and heating piping systems with the heater as a heat exchanger[2]. It uses hot water from a boiler (perhaps directly inside it.) or a solar-heated water circuit to heat itself[2]. Heat is transferred directly by conduction through the exchanger material that separates the media used in and on[2].

It is quite broad to consider the everyday use of heat exchangers. One can say air conditioning systems, petrochemical systems, power plants, cosmetic industries, shipbuilding, food processing, paper industries, and more. In general, it can be easily concluded that heat exchanger is a technology that makes life easier and is used almost everywhere every day.

2.1.2 Fouling of Heat Exchangers

Fouling can be defined as the substance accumulation on the surface of the heat exchanger, and this substance should be removed[1]. Most of the time, this growth leads to unwanted material collection and performance drops in the system. It can also happen synthetically, but in chemical production plants; other than that, it also happens in the human body wherein we deposit cholesterol, and it proliferates to the creation of plaque on the walls of arteries to make arteriosclerosis. To prevent this effect, one can use thin films that prevent accumulation in the inside surface of the heat exchanger, use different materials on piping, and filter the fluid may also be other options to prevent fouling.

2.1.3 Working Principle of Heat Exchanger?

Heat exchangers abide by the second thermodynamics rule, indicating that heat flows from one body to another based on differential temperatures [1]. In molecular motion, due to thermodynamics is the vibration of the molecules, we expect the higher energetic or oscillating particles to exert energy on the lower ones[1]. This is a cooling medium, and whether it is water, steam, acetic acid, or methanol, all are carried via tubes within heat exchanger piping and for a shell and tube inside shell construction. For plate type, one at the heat inlet, the other at the cold inlet[1].

2.1.4 What are the types of Heat Exchangers that are available?

One can think of various heat exchanger types or examples, but only three types can be said as widely used around the globe. These three main types are

1. Shell and Tube Heat Exchanger[2]
2. Plate Type Heat Exchanger[2]
3. Air Cooled (finned) heat exchangers - with no permanent cool water source available[2].

Also, polymer-based heat exchangers and compact heat exchangers(similar to air-cooled).

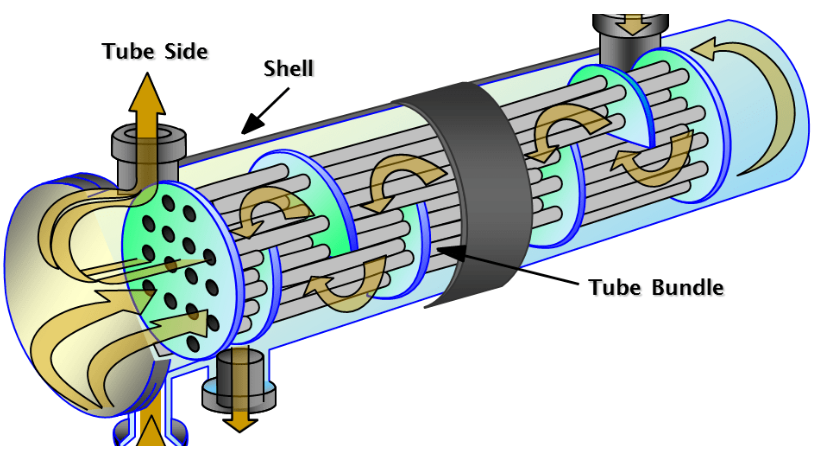
What are the advantages and disadvantages also characteristics of these different types of heat exchangers?

2.1.5 Shell and Tube Heat Exchanger

Shell-and-tube heat exchangers are the most versatile[1]. They are used in various different areas, such as; process industries, nuclear power stations as condensers, steam generators in water reactor power plants, in many alternative energy applications[1].

Shell-and-tube heat exchangers are easy to maintain due to relatively large ratios of heat transfer area to volume and weight[1]. Since widely used, it offers high-pressure types and can be used with high-pressure drop streams[1].

It is built by covering a cylindrical shell with mounted round tubes with tubes parallel to the shell[1]. One of the fluids flows inside the tubes, while the other flows through or across the axial path of the exchanger[1]. It has significant components, such as tubes (tube bundles), shells, front-end heads, rear-end heads, baffles, and tube sheets. One illustration can be given as follows[1].



(Figure 1: Shell-and-Tube Type Heat Exchanger)[4]

Advantages of the shell-and-tube exchanger are[3]:

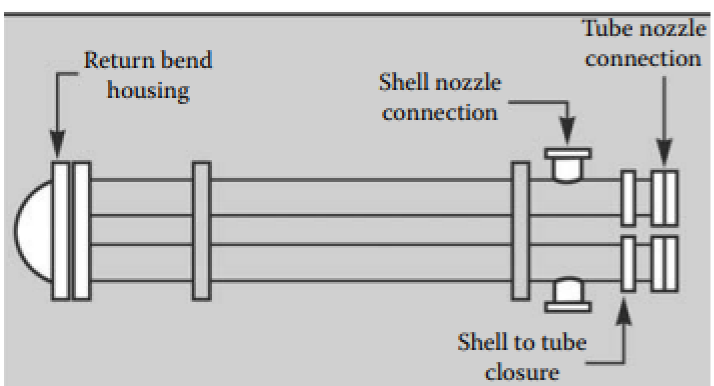
- Costs less than the plate type coolers
- Pressure drop over the tube cooler is less
- One can use anodes with the entire cooling framework and prevent erosion
- Easy to maintain
- Can be used at high temperatures, weight, and pressure

Disadvantages are[3]:

- Heat exchange is less effective compared to plate type
- Cannot expand the capacity of the tube
- It is big, so requires a vast amount of spatial field
- Cleaning sometimes be rough due to being big

2.1.6 Double Pipe Heat Exchanger

A typical double-pipe heat exchanger has one pipe placed concentrically inside one other pipe of a larger diameter with appropriate fittings adapted to the direction of the flow from one section to another as given below:



(Figure 2: Double-pipe hairpin heat exchanger)[1]

The inner pipe in figure 2 is connected by U-shaped return bends enclosed in a return-bend housing[1]. Double-pipe heat exchangers can be arranged into different series and parallel adjustments to meet appropriate pressure drop and mean temperature difference requirements[1]. The double-pipe system is widely used for sensible heating or cooling process fluids, such as acetic acid and ethanol, where small heat transfer areas are sufficient and required[1]. This setup is also very suitable for high-pressure fluids on both sides or only one side due to the small diameter of the pipes[1]. An essential disadvantage of the double-pipe is being expensive per heat transfer surface area and bulky[1].

The double-pipe heat exchangers are sometimes referred to as hairpin heat exchangers due to their shape[1]. It can be used when one stream is a gas, high viscosity liquid, or small in volume[1]. These heat exchangers can be used under harsh conditions, such as fouling conditions, due to ease of maintenance and care. It can also be finned, so the heat transfer can be increased[1]. These fins are the most efficient when the film coefficient is the minimum. Typical outer pipe inside diameter ranges from 50-400 mm, and the nominal length of each hairpin is around 1.5-12.0 m[1]. The outer diameter of the inner tube can also differ between 10 to 100 mm[1]. Demonstration of series and parallel hairpins to visualize is also essential, and therefore here in figure 3, one can see a series arranged double-pipe heat exchanger as below[1]:

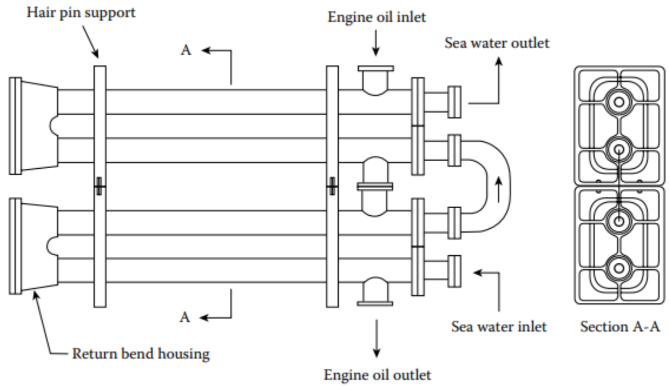


FIGURE 7.4
Two hairpin sections arranged in series.

(Figure 3: Two hairpin sections arranged in series)[1]

Advantages of the double-pipe exchanger are[5]:

- Suitable for high-pressure applications
- Modular type construction
- Can be welded easily
- Easy to construct, clean and relatively cheap due to small sizes (per size price higher but not necessary)

Disadvantages are[5]:

- Modular but dismantling time-consuming
- Can leak and may not be easily found

Lastly, the double pipe can be used in refrigeration devices which is actually what we see behind refrigerators, it is indeed a double-pipe heat exchanger[5].

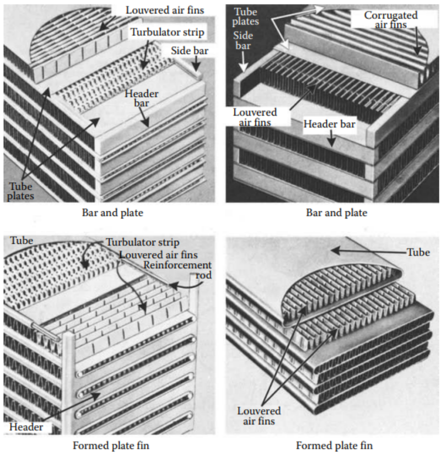
2.1.6 Compact Heat Exchanger

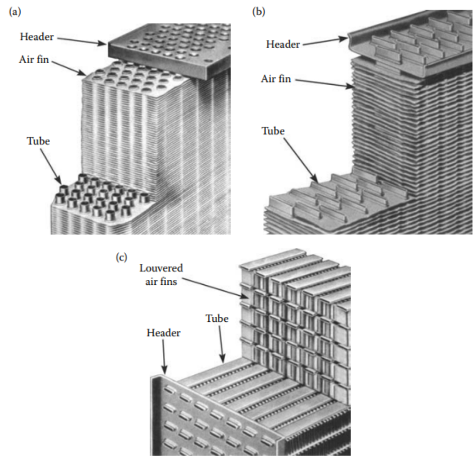
Compact heat exchangers can be defined as plate-type, tube-fin type, and regenerative type, with tube bundles being in small diameters and the latter generally applied to gas flow network piping systems[1]. To identify as a compact heat exchanger, it is not necessary to have a different shape or structure of the system rather a tube bundle having a surface area density greater than about 700 $\frac{m^2}{m^3}$. In compact heat exchangers, the heat transfer surface area is increased by fins to increasing the heat transfer rate by increasing the surface area per volume[1]. There are other transmitting versions available such as micro heat exchangers, which have $\sigma\ (surface\ area\ density) > 10000\ \frac{m^2}{m^3}$. Compact heat exchangers are widely used in gas network systems, condensers, cryogenics processes, 80K lab freezers, oil coolers, energy recovery and, etc. [1].

Heat Transfer Enhancement is the most important part of this exchanger, in which augmented surfaces can be increased in the following ways[1]:

- The heat transfer coefficient can be increased with a lagging increase in the surface area.
- The heat transfer coefficient can be lagging while surface area increases dramatically.
- Both heat transfer coefficient and surface area can be increased together.

Tube and Plate-fin heat exchangers are illustrated as follows[1]:





(Figure 4.1:Plate-fin heat exchanger - Figure 4.2: Tube-fin heat exchanger.)[1]

2.1.7 Polymer Heat Exchanger

Polymer heat exchangers are mainly used for their fouling and corrosion-resistive characteristics, and the polymers offer low maintenance cost, water consumption, volume, and space[1]. These positive characteristics make polymer heat exchangers more competitive in some fields than metallic heat exchangers[1]. Due to low thermal conductivity, usually not considered for heat exchangers, but still useful for specific heat exchanger applications, such as on polymer matrix composites[1].

Some examples of monolithic polymers used as polymer heat exchangers are given[1]:

- Polyvinylidene difluoride (PVDF) is a pure thermoplastic fluoropolymer since fluoropolymers are known to be resistant to chemical corrosion. It is used for its high purity, strength, and resistance to solvents and acids.

- Teflon or Polytetrafluoroethylene (PTEE) is chemically resistant to nearly all fluids. It can work up to $204^{\circ}C$.

these monolithic polymers and others yet to discover are mainly protective against chemicals, therefore, can be used in heat exchangers where chemicals are used with acids in them[1].

2.1.8 Plate Heat Exchanger

Plate heat exchangers consisted of the plate and frame and were introduced mainly for the food industry when they first entered the business in the 1930s due to the ease of cleaning the plate and structure [1]. The design of the Plate came to its main-used design with more effective plate geometries, assembly styles, and new plate materials[1]. Various design options and a wide range of possible applicable services made its use comparable for some instances overlapping and succeeding in winning against shell-and-tube heat exchangers[1]. In the level of low to medium pressure liquid to liquid heat transfer applications, it is a solid alternative to shell-and-tube type heat exchangers[1]. Plate Heat Exchangers are highly specialized in the design, even though the variety of designs available for the arrangements and plates for various duties, unlike the shell-and-tube heat exchanger, data and methods are lacking, and novel designs are still the property of companies and their computational tools are sold with high costs[1].

2.1.8.1 Mechanical Features

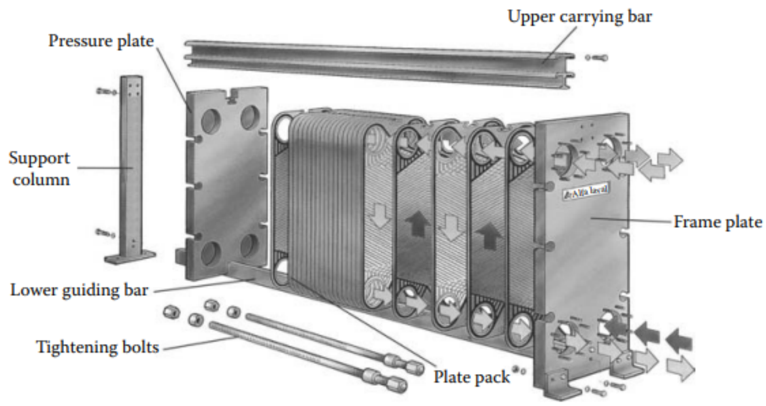


FIGURE 11.1
Gasketed-plate heat exchangers. (Courtesy of Alfa-Laval Thermal AB.)

(Figure 5: Plate heat exchangers.)[1]

From figure 5, it can be seen that the elements of the frame of the plate and frame of the -plate heat exchanger are a fixed plate, compression plate, pressing equipment, and ports that connect each to one other[1]. The heat transfer surface of the series is composed of plates composed of parts for fluid entry and exit to the four corners[1]. The flow pattern is also should be considered in the plate heat exchanger, and the pattern can be given in figure 6, below[1]:

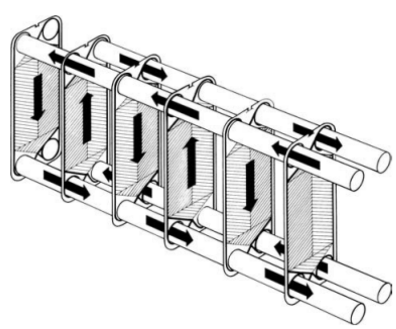


FIGURE 11.3
Flow diagram in a single-pass counterflow arrangement. (Courtesy of Alfa-Laval Thermal AB.)

(Figure 6: Flow diagram in a single-pass counterflow arrangement.)[1]

A Bundle of plates is used to build a plate heat exchanger, the plates are pressed together, and with the holes with specific chevron angles, these plates on the corners form a continuous fight, which leads to media from the inlets into the plate package[1]. By calibrating precision tightening devices, the tightening pressure can be put to the desired level. These passages between the plate and corner ports are arranged so that two heat transfer media can flow through alternate channels. The flow is always Countercurrent flow[1]. Tables for the plate types and materials are given in Tables 11.1 and 11.2[1].

Limitations, more often referred to as capabilities of Plate heat exchangers, are limited due to the plates of the heat exchanger. The restrictions for the operating temperature to act linearly is ($150^{\circ}C - 260^{\circ}C$) and pressures (at minimum 25-30 bar.) Moreover, one cannot has a pressure of more than 2.5 MPa; the exchangers' size is also limited by being no larger than 1500 m^2 [1].

One can also have different flow patterns, such as shown in figure 7 below:

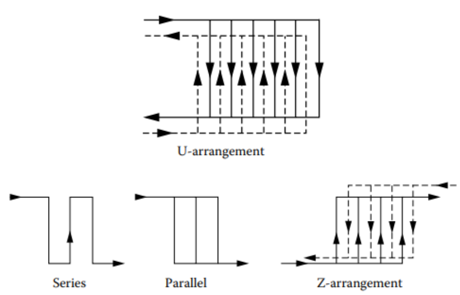


FIGURE 11.9
Flow pattern: (a) schematic of a U-type arrangement—counterflow, single-pass flow (1 × 6/1 × 6) (b) Z-arrangement (1 × 4/1 × 4 configuration).

(Figure 7: Flow Pattern.)[1]

Plate heat exchangers are[3]:

- Simple and compact
- Heat exchange effectiveness is more
- Easy to clean out
- Easy to maintain and dismantle
- Higher Reynolds number helps to achieve higher heat transfer rate

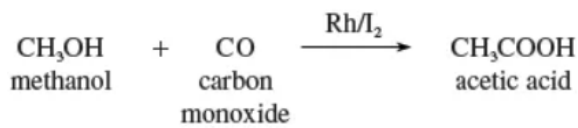
Plate heat exchangers also have negative effects, and some are[3]:

- Initial cost is high for titanium plates, in the project titanium plates also satisfied the conditions are considered.
- Spillage test is hard to conduct and cannot see any leakage easily.
- Maintenance and testing are hard to measure
- Pressure drop at plate cooler is higher than tube cooler.

2.2 Acetic Acid-Water Mixture

Acetic acid (CH_3COOH), also known as ethanoic acid, is the most notable of the carboxylic acids family[6]. A dilute solution of acetic acid can be produced via fermentation and oxidation of natural carbohydrates, called vinegar; a salt, ester, or acylal of this acid is called acetate. Acetate is widely used in durable and flexible glasses material; most quality glasses are made from acetate[6]. Acetate is also used in cosmetics, foods, cleaning supplies, and textiles[6]. Acetic acid is directly used to make plastics, cellulose acetate, photographic films, and textiles[6]. It is used as a solvent for resins, paints, and lacquers. Moreover, acetic acid is also a biologically important metabolic intermediate[6].

Nowadays, acetic acid is produced by methanol carbonylation catalysis involving rhodium-iodine[6]. The process is mainly done by Monsanto[6].



(Figure 8: Acetic Acid Production Reaction) [6]

Due to non-dilute solutions (~25%)[7] being extremely corrosive to the surroundings, it is important to pick heat exchanger equipment that won't be corroded with acetic acid. However, it can also be assumed in an ideal scenario that it won't be corrosive[7].

Acetic acid-water diluted solutions are made to have acetate or to be able to react with different products to get high-quality produce[8]. One can use 30% acetic acid to solve agarwood essence and different facets of vanilla to get the most out of the flavor, rather than getting only one facet of the vanilla. So, it can be used in high-quality factories-ateliers or as an intermediary to dilute after.

3. Result

3.1 Equations

To calculate the heat transfer coefficient, Kumar's Correlation is used through this design[1]. The formulation is given in Equation 1.

$$\frac{hD_h}{k} = C_h\left(\frac{D_hG_c}{\mu}\right)^n\left(\frac{c_p\mu}{k}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.17}$$

(Equation 1: Kumar’s Proposed Correlation)[1]

C_h, and n are constants that change with Chevron angle and Reynolds Number. In Figure 10, the constants are shown as

Constants for Single-Phase Heat Transfer and Pressure Loss Calculation in Gasketed-Plate Heat Exchangers[2,10]

Chevron Angle (degree)	Heat Transfer			Pressure Loss		
	Reynolds Number	C_h	n	Reynolds Number	K_p	m
≤30	≤10	0.718	0.349	<10	50.000	1.000
	>10	0.348	0.663	10–100	19.400	0.589
				>100	2.990	0.183
45	<10	0.718	0.349	<15	47.000	1.000
	10–100	0.400	0.598	15–300	18.290	0.652
	>100	0.300	0.663	>300	1.441	0.206
50	<20	0.630	0.333	<20	34.000	1.000
	20–300	0.291	0.591	20–300	11.250	0.631
	>300	0.130	0.732	>300	0.772	0.161
60	<20	0.562	0.326	<40	24.000	1.000
	20–400	0.306	0.529	40–400	3.240	0.457
	>400	0.108	0.703	>400	0.760	0.215
≥65	<20	0.562	0.326	50	24.000	1.000
	20–500	0.331	0.503	50–500	2.800	0.451
	>500	0.087	0.718	>500	0.639	0.213

Source: From Saunders, E. A. D., *Heat Exchangers—Selection, Design, and Construction*, John Wiley & Sons, New York, 1988; Kumar, H., *Inst. Chem. Symp. Series*, No. 86, 1275–1286, 1984.

(Figure 9: Related Constants for Correlation)[1].

Also, one of the parameters G_c is channel mass velocity and found by;

$$G_c = \frac{\dot{m}}{N_{cp} * b * l_w} \quad \text{[equation 2]}$$

and b is plate spacing, l_w is horizontal length, N_{cp} is the number of channels per pass which is obtained from

$$N_{cp} = \frac{N_t - 1}{2 * N_p}$$

Also D_h is the hydraulic diameter defined as,

$$D_h = \frac{2 * b}{\varphi}$$

where φ is the enlargement factor which is the proportion of the given area for the plate that is generally provided by the manufacturer to the projected area. The ratio is found as

$$\varphi = \frac{A_1}{A_{1p}}$$

Where A_{1p} is can be found as

$$A_{1p} = (l_v - p) * l_w$$

The Reynolds number for this relationship can be expressed as

$$Re = \frac{G_c * D_h}{\mu}$$

There are two kinds of pressure drops. They are the pressure drop in channels Δp_c and the pressure drop in ports Δp_p. The following relation for the pressure drop in the channel is applied.

$$\Delta p_c = 4 * f * \frac{l_{eff} * N_p}{D_h} * \frac{G_c^{\ 2}}{2 * \rho} * (\frac{\mu_b}{\mu_w})^{-0.17}$$

where l_{eff} is the effective length which equals to l_v. μ_b is the viscosity at the bulk fluid temperature, and μ_w is the viscosity at the wall temperature.

The relation for friction factor f is obtained by

$$f = \frac{K_p}{Re^m}$$

The following relation for the pressure drops in ports will also use

$$\Delta p_p = 1.4 * N_p * \frac{G_c^{\ 2}}{2 * \rho}$$

Where G_p is found by

$$G_p = \frac{\dot{m} * 4}{\pi * D_p}$$

Where D_p is the port diameter.

So, the total pressure drop is calculated by summing these two pressure drop values.

$$\Delta p_t = \Delta p_c + \Delta p_p$$

The correlation and pressure drop calculation should be made for two conduits separately. So, in the end, we would have h_h, the heat transfer coefficient for the hot fluid and h_c the heat transfer coefficient for the cold fluid.

So, the following equation will be used to improve the heat transfer coefficient.

$$\frac{1}{U_c} = \frac{1}{h_c} + \frac{1}{h_h} + \frac{t}{k_s}$$

$$\frac{1}{U_f} = \frac{1}{h_c} + \frac{1}{h_h} + \frac{t}{k_s} + R_f$$

Where U_c is the overall clean heat transfer coefficient, U_f is the overall fouled heat transfer coefficient, and R_f is the thermal resistance due to fouling.

Some of the recommended fouling resistances are shown in figure 10.

TABLE 11.4

Recommended Fouling Factors for Plate Heat Exchangers

Service	Fouling Factor, m² · K/W
Water	
Demineralized or distilled	0.0000017
Soft	0.0000034
Hard	0.0000086
Cooling tower (treated)	0.0000069
Sea (coastal) or estuary	0.000086
Sea (ocean)	0.000052
River, canal, tube well, etc.	0.000086
Engine jacket	0.0000103
Steam	0.0000017
Lubricating oils	0.0000034–0.0000086
Vegetable oils	0.0000017–0.0000052
Organic solvents	0.0000017–0.0000103
General process fluids	0.0000017–0.00000103

Source: From Raju, K. S. N. and Jagdish, C. B., *Low Reynolds Number Flow Heat Exchangers*, Hemisphere, Washington, DC, 1983; Cooper, A. et al., *Heat Transfer Eng.*, Vol. 1, No. 3, 50–55, 1980. With permission.

(Figure 10: Fouling Resistances)[1]

After obtaining this heat transfer coefficient, the heat transfer rate can be calculated by

$$Q = U * A_e * \Delta T_{LM}$$

Where ΔT_{LM} is the log mean temperature difference, and A_e is the effective area which is equals to $A_e = A_1 * N_e$, where N_e is the effective number of plates which is equal to $N_e = N - 2$.

3.2 Sample Calculation

Before starting calculations there are design standards that should be provided priorly. In the Figure 11, those conditions are shown.

Some Useful Data on Plate Heat Exchangers

Unit		
Largest size	1,540 m²	
Number of plates	Up to 700	
Port size	Up to 39 cm	
Plates		
Thickness	0.5–1.2 mm	
Size	0.03–2.2 m²	
Spacing	1.5–5.0 mm	
Contact points	For every 1.5–20 cm²	Depends on plate size and type of corrugations
Operation		
Pressure	0.1–1.5 MPa	Up to 2.5 MPa in special cases
Temperature	–25°C to 150°C –40°C to 260°C	With rubber gaskets
Port velocities	5 m/s	With compressed asbestos fiber gaskets
Channel flow rates	0.05–12.5 m³/h	
Maximum flow rates	2,500 m³/h	
Performance		
Temperature approach	As low as 1°C	
Heat recovery	As high as 90%	
Heat transfer coefficients	3,000–7,000 W/m² °C	Water-to-water duties with normal fouling resistance
Number of transfer units	0.4–4.0	
Optimum pressure drops	30 kPa per NTU	

Source: From Raju, K. S. N. and Jagdish, C. B., *Low Reynolds Number Flow Heat Exchangers*, Hemisphere, Washington, DC, 1983. With permission.

(Figure 11: Design Standards)[1]

Also, the thermal conductivity for different plate materials is shown in Figure 13.

Plate Materials

Material	Thermal Conductivity (W/m² · K)
Stainless steel (316)	16.5
Titanium	20
Inconel 600	16
Incolay 825	12
Hastelloy C-276	10.6
Monel 400	66
Nickel 200	66
9/10 Cupro-nickel	52
70/30 Cupro-nickel	35

Source: From Raju, K. S. N. and Jagdish, C. B., *Low Reynolds Number Flow Heat Exchangers*, Hemisphere, Washington, DC, 1983. With permission.

(Figure 12: Thermal Conductivity of Plate Materials)[1]

Port Size (P), Thickness (t), and Plate Spacing (S) are iterated through our calculations will all the possible combinations. For an instance of calculation, and for the final design, the values are taken as 0.076 m, 0.00102 m, and 0.0049 m respectively. For the dimensions of our plates, the vertical length (l_v), and the horizontal length (l_w) are taken as 0.36 m, and 0.54 m. The chevron angle is taken as 45°. By using those values an initial plate area is calculated at 0.1962 m^2 which also includes reliefs due to make the chevron regions. Since we designed a simple one-pass/one-pass heat exchanger we take the number of passes (N_p) for cooling water, and hot fluid as 1. In Table 1 below, the parameters are shown.

(Table 1: Initial Geometric Parameters for the plate)

Parameter	Magnitude
P	0.076 m
t	0.00102 m
S	0.00495 m
l_v	0.36 m
l_w	0.54 m
Chevron Angle	45°
A_1	0.1962 m^2
N_p	1
k_s	20 W/(m^2 * K)

The maximum pressure drop is 25 psi. The inlet temperature of the hot fluid (T_{hi}) is 100°C. The outlet temperature of the hot fluid (T_{ho}) is 45°C. The inlet temperature of the cold fluid (T_{ci}) is 25°C. The outlet temperature of the cold fluid (T_{co}) should not exceed 35°C. So, to calculate some useful flowing fluid parameters, it is assumed that the outlet temperature is equal to 35°C which is the maximum allowable temperature value.

Log Mean Temperature Difference (LMTD) can be found by using the following formula.

$$LMTD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{ln(\frac{(T_{hi} - T_{co})}{(T_{ho} - T_{ci})})}$$

This formula is designed for the counter-current flow, by substituting the parameters into their places.

$$LMTD = \frac{(100-35)-(45-25)}{ln(\frac{(100-35)}{(45-25)})}$$

To calculate flowing fluid parameters, firstly it is assumed that the acetic acid–water solution is treated as it is forming an ideal solution. So, all the physical properties can be calculated by taking the ratios of the components that are forming the mixture. Let θ_{mix} any physical property for the mixture and θ_i is the pure component properties. With assumption θ_{mix} can be calculated by the following formulation.

$$\theta_{mix} = \sum \theta_i * w_i$$

w_i is the weight fraction of one component compared to the overall mixture.

(Table 2: Flowing Material Parameters)[9][10]

Parameters	Magnitude
$C_{p,\ mix}$	7774.85 J/(kg*K)
$C_{p,\ water}$	4178 J/(kg*K)
ρ_{mix}	980.4 kg/m^3
ρ_{water}	995.65 kg/m^3
μ_{mix}	$4.548*10^{-4}$ Pa*s
μ_{water}	$8.034*10^{-4}$ Pa*s
k_{mix}	0.5096 W/(m*K)
k_{water}	0.6172 W/(m*K)
Pr_{mix}	6.939
Pr_{water}	5.438

Pr_{mix} , and Pr_{water} are Prandtl numbers which are calculated by using following relation $\frac{\mu * C_p}{k}$

For convenience and calculation habit the unit of the mass flow rate of the mixture ($\dot{m}_{mix}$) is converted to SI units.

$$\dot{m}_{mix} = \frac{13000}{3600\ s} \frac{kg}{hr} \frac{hr}{1} = 3.611 \frac{kg}{s}$$

The heat that should be extracted from the hot fluid is calculated by using the following equation.

$$Q = \dot{m} * C_p * (T_i - T_o)$$

$$Q = \dot{m}_{mix} * C_{p,\,mix} * (T_{hi} - T_{ho}) = 3.611 * 7774.85 * (100 - 45) = 1.544 * 10^6 \frac{J}{s}$$

$$\dot{m}_{water} = \frac{Q}{C_{p,\,water} * (T_{co} - T_{ci})} = \frac{1.544 * 10^6}{4178 * (35 - 25)} = 36.96 \frac{kg}{s}$$

With the 210 number of plates the following calculations are made.

3.3 Code Script

```
[ ] import numpy as np
    import math
    import pandas as pd
    import matplotlib.pyplot as plt
    import itertools
    from google.colab import drive
    drive.mount('/content/drive')
    %cd /content/drive/MyDrive/Data
```

```
[ ] def Ch(Re):
      if Re < 10:
        return 0.718
      elif Re < 100:
        return 0.4
      else:
        return 0.3

    def n(Re):
      if Re < 10:
        return 0.349
      elif Re < 100:
        return 0.598
      else:
        return 0.663

    def Kp(Re):
      if Re < 15:
        return 47
      elif Re < 300:
        return 18.290
      else:
        return 1.441

    def m(Re):
      if Re < 15:
        return 1
      elif Re < 300:
        return 0.652
      else:
        return 0.206
```

Design Spesifications

```
[ ] port_size = np.linspace(0.001,0.39,100) # in m
    number_of_plates = np.linspace(3
                                   ,700,698)
    plate_thickness = np.linspace(0.0005,0.0012,71) # in m
    plate_spacing = np.linspace(0.0015,0.005,351) # in m DONT NEED, WILL BE CALCULATED LATER
    MAX_PRESSURE_DROP = 25 # psi
```

```
[ ] df = pd.read_csv("DESIGN PARAMETERS COMBINED.csv", index_col = 0)
```

```
[ ] df
```

	PORT_SIZE	THICKNESS	PLATE_SPACING
0	0.001000	0.0005	0.0015
1	0.004929	0.0005	0.0015
2	0.008859	0.0005	0.0015
3	0.012788	0.0005	0.0015
4	0.016717	0.0005	0.0015
...	...	...	...
2492095	0.374283	0.0012	0.0050
2492096	0.378212	0.0012	0.0050
2492097	0.382141	0.0012	0.0050
2492098	0.386071	0.0012	0.0050
2492099	0.390000	0.0012	0.0050

2492100 rows × 3 columns

```
effective_number_of_plates = number_of_plates - 2
NUMBER_OF_PASSES = 1 # Np
number_of_channel_per_pass = (number_of_plates - 1)/(2*NUMBER_OF_PASSES)
```

Design Goals

```
[ ] # Hot Fluid
    Thi = 100 # degree celcius
    Tho = 45 # degree celcius
    # Cold Fluid
    Tci = 25 # degree celcius
    Tco = 35 # degree celcius
    LOG_MEAN_TEMPERATURE_DIFF = ((Thi-Tco) - (Tho-Tci))/math.log((Thi-Tco)/(Tho-Tci))
    print("The Log Mean Temperature Difference is :", LOG_MEAN_TEMPERATURE_DIFF)
```

```
The Log Mean Temperature Difference is : 38.17911105427177
```

Material Parameters

```
[ ] CP_MIXTURE = 7774.85 # J/kg*K
    CP_WATER = 4178 # J/kg*K

    DENSITY_MIXTURE = 980.3987 # kg/m3
    DENSITY_WATER = 995.65 # kg/m3

    VISCOSITY_MIXTURE = 4.548*10**(-4) # Pa*s # Obtained from other file
    VISCOSITY_WATER = 8.034*10**(-4) # Pa*s

    THERMAL_CONDUCTIVITY_MIXTURE = 0.5096 # W/mK
    THERMAL_CONDUCTIVITY_WATER = 0.6172 # W/mK

    PRANDTL_NUMBER_MIXTURE = VISCOSITY_MIXTURE*CP_MIXTURE/THERMAL_CONDUCTIVITY_MIXTURE
    PRANDTL_NUMBER_WATER = VISCOSITY_WATER*CP_WATER/THERMAL_CONDUCTIVITY_WATER
```

```
[ ] PRANDTL_NUMBER_WATER
```

```
5.438440051847053
```

```
[ ] PRANDTL_NUMBER_MIXTURE
```

```
6.938779003139718
```

Flow Parameters

```
[ ] mass_flow_rate_of_mixture = round(13000/3600,3) # kg/s
    Q = round(mass_flow_rate_of_mixture*CP_MIXTURE*(Thi-Tho),3) # J/s
    mass_flow_rate_of_water = round(Q/(CP_WATER*(Tco-Tci)),3) # kg/s
    print(f"Mass Flow Rate of Acetic Acid Mixture is {mass_flow_rate_of_mixture} kg/s\nHeat Transfer is {Q} J/s\nMass Flow Rate of Cooling Water is {mass_flow_rate_of_water} kg/s")
```

```
Mass Flow Rate of Acetic Acid Mixture is 3.611 kg/s
Heat Transfer is 1544124.084 J/s
Mass Flow Rate of Cooling Water is 36.958 kg/s
```

Additional assumed parameters and same calculated parameters

```
[ ] # Thermal conductivy of the material
    THERMAL_CONDUCTIVITY_OF_MATERIAL = 20 # W/m^2K
    vertical_port_distance = 0.6 # m lv ALSO EFFECTIVE FLOW LENGTH
    effective_channel_width = 0.9 # m lw
    chevron_angle = 45 # degrees
    A1 = 0.545 # m^2
    A1p = (vertical_port_distance - port_size) * effective_channel_width
    enlargement_factor = A1/A1p
```

```
[ ] ratio = 0.6

    A1 = A1 * ratio**2
    vertical_port_distance = vertical_port_distance * ratio
    effective_channel_width = effective_channel_width * ratio
```

```
[ ] df["A1"] = A1
    df["A1p"] = (vertical_port_distance - df["PORT_SIZE"]) * effective_channel_width # change
    df["E_FAC"] = df["A1"]/df["A1p"]
```

```
[ ] df
```

	PORT_SIZE	THICKNESS	PLATE_SPACING	A1	A1p	E_FAC
0	0.001000	0.0005	0.0015	0.1962	0.193860	1.012071
1	0.004929	0.0005	0.0015	0.1962	0.191738	1.023270
2	0.008859	0.0005	0.0015	0.1962	0.189616	1.034721
3	0.012788	0.0005	0.0015	0.1962	0.187495	1.046430
4	0.016717	0.0005	0.0015	0.1962	0.185373	1.058408
...	...	...	...	...	...	...
2492095	0.374283	0.0012	0.0050	0.1962	-0.007713	-25.438472
2492096	0.378212	0.0012	0.0050	0.1962	-0.009835	-19.950083
2492097	0.382141	0.0012	0.0050	0.1962	-0.011956	-16.409672
2492098	0.386071	0.0012	0.0050	0.1962	-0.014078	-13.936459
2492099	0.390000	0.0012	0.0050	0.1962	-0.016200	-12.111111

2492100 rows × 6 columns

Calculating Parameters for Each Case and Adding Them to DataFrame

Dh = Hydraulic Diameter Ach = One Channel Flow Area

```
[ ] # Calculating Dh
    df["Dh"] = 2*df["PLATE_SPACING"]/df["E_FAC"]
    df["Ach"] = df["PLATE_SPACING"] * effective_channel_width
```

```
[ ] df
```

	PORT_SIZE	THICKNESS	PLATE_SPACING	A1	A1p	E_FAC	Dh	Ach
0	0.001000	0.0005	0.0015	0.1962	0.193860	1.012071	0.002964	0.00081
1	0.004929	0.0005	0.0015	0.1962	0.191738	1.023270	0.002932	0.00081
2	0.008859	0.0005	0.0015	0.1962	0.189616	1.034721	0.002899	0.00081
3	0.012788	0.0005	0.0015	0.1962	0.187495	1.046430	0.002867	0.00081
4	0.016717	0.0005	0.0015	0.1962	0.185373	1.058408	0.002834	0.00081
...	...	...	...	...	...	...	...	...
2492095	0.374283	0.0012	0.0050	0.1962	-0.007713	-25.438472	-0.000393	0.00270

Mass Flow Rate Per Channel

```
[ ]  initial_number_of_plates = 10

     design_list = []
     final = pd.DataFrame(columns = ['PORT_SIZE', 'THICKNESS', 'PLATE_SPACING', 'A1', 'A1p', 'E_FAC', 'Dh',
            'Ach', 'Gch', 'Reh', 'Chh', 'nh', 'Nuh', 'hh', 'Gcc', 'Rec', 'Chc',
            'Nuc', 'hc', 'U', 'Uf', 'Q', 'Qf', 'Kph', 'Kpc', 'mh', 'mc', 'fh', 'fc', 'deltaPch',
            'deltaPcc', 'Number_of_plates'])
     i = 1
     while initial_number_of_plates <= 210:
       print(initial_number_of_plates)
       effective_number_of_plates = initial_number_of_plates - 2 # Ne
       number_of_channel_per_pass = (initial_number_of_plates - 1)/(2*NUMBER_OF_PASSES) # Ncp

       # Hot Fluid Parameters
       hot_mass_flow_rate_per_channel = mass_flow_rate_of_mixture/number_of_channel_per_pass
       df["Gch"] = hot_mass_flow_rate_per_channel/df["Ach"]
       df["Reh"] = df["Gch"]*df["Dh"]/VISCOSITY_MIXTURE
       df["Chh"] = df["Reh"].apply(Ch)
       df["nh"] = df["Reh"].apply(n)
       df["Nuh"] = df["Chh"]*df["Reh"]**df["nh"]*PRANDTL_NUMBER_MIXTURE**(1/3)
       df["hh"] = df["Nuh"] * THERMAL_CONDUCTIVITY_MIXTURE/df["Dh"]

       # Cold Fluid Parameters
       cold_mass_flow_rate_per_channel = mass_flow_rate_of_water/number_of_channel_per_pass
       df["Gcc"] = cold_mass_flow_rate_per_channel/df["Ach"]
       df["Rec"] = df["Gcc"]*df["Dh"]/VISCOSITY_WATER
       df["Chc"] = df["Rec"].apply(Ch)
       df["nh"] = df["Reh"].apply(n)
       df["Nuc"] = df["Chc"]*df["Rec"]**df["nh"]*PRANDTL_NUMBER_WATER**(1/3)
       df["hc"] = df["Nuc"] * THERMAL_CONDUCTIVITY_WATER/df["Dh"]

       df["U"] = (1/df["hh"] + 1/df["hc"] + df["THICKNESS"]/THERMAL_CONDUCTIVITY_OF_MATERIAL)**(-1)
       df["Uf"] = (1/df["U"] + 0.0000034)**(-1)


       Ae = effective_number_of_plates * A1

       df["Q"] = df["U"] * Ae * LOG_MEAN_TEMPERATURE_DIFF
       df["Qf"] = df["Uf"] * Ae * LOG_MEAN_TEMPERATURE_DIFF
       # Fouiling_Factor

       df["Kph"] = df["Reh"].apply(Kp)
       df["Kpc"] = df["Rec"].apply(Kp)
       df["mh"] = df["Reh"].apply(m)
       df["mc"] = df["Rec"].apply(m)
```

```
    df["Q"] = df["U"] * Ae * LOG_MEAN_TEMPERATURE_DIFF
    df["Qf"] = df["Uf"] * Ae * LOG_MEAN_TEMPERATURE_DIFF
    # Fouiling_Factor

    df["Kph"] = df["Reh"].apply(Kp)
    df["Kpc"] = df["Rec"].apply(Kp)
    df["mh"] = df["Reh"].apply(m)
    df["mc"] = df["Rec"].apply(m)


    df["fh"] = df["Kph"]/(df["Reh"]**df["mh"])
    df["fc"] = df["Kpc"]/(df["Rec"]**df["mc"])

    df["deltaPch"] = (4*df["fh"]*vertical_port_distance*initial_number_of_plates/df["Dh"]*df["Gch"]**2/(2*DENSITY_MIXTURE))*0.000145038
    df["deltaPcc"] = (4*df["fc"]*vertical_port_distance*initial_number_of_plates/df["Dh"]*df["Gcc"]**2/(2*DENSITY_WATER))*0.000145038
    df["Gph"] = (4 * mass_flow_rate_of_mixture/(math.pi*df["PORT_SIZE"]**2))
    df["Gpc"] = (4 * mass_flow_rate_of_water/(math.pi*df["PORT_SIZE"]**2))

    df["deltaPph"] = 1.4*NUMBER_OF_PASSES*df["Gph"]**2/(2*DENSITY_MIXTURE)*0.000145038
    df["deltaPpc"] = 1.4*NUMBER_OF_PASSES*df["Gpc"]**2/(2*DENSITY_WATER)*0.000145038
    df["deltaPth"] = df["deltaPch"] + df["deltaPph"]
    df["deltaPtc"] = df["deltaPcc"] + df["deltaPpc"]


    tobeappened = list(df[(min(df["Q"]) == df["Q"])].values[0])
    tobeappened.insert(0,initial_number_of_plates)
    design_list.append(tobeappened)


    #print(df[min(df["deltaPpc"]) == df["deltaPpc"]][["deltaPcc","deltaPpc"]])
    da = df[((df["deltaPch"] + df["deltaPph"]) < 25) & ((df["deltaPcc"] + df["deltaPpc"]) < 25) & (df["Qf"] > 1.55*10**6)]
    da["Number_of_plates"] = initial_number_of_plates
    try:
      da = da[da.Q == min(da.Q)]
      print(da)
      final = pd.concat([final,da])
    except:
      pass


    i += 1
    initial_number_of_plates += 100

final
```

```
10
110
210
        PORT_SIZE  THICKNESS  PLATE_SPACING      A1       A1p     E_FAC  \
1859719  0.075657    0.00102        0.00495  0.1962  0.153545  1.277798

               Dh       Ach        Gch         Reh  ...        fc  deltaPch  \
1859719  0.007748  0.002673  12.927431  220.224148  ...  0.330265  0.261908

          deltaPcc         Gph          Gpc  deltaPph  deltaPpc  deltaPth  \
1859719  16.436231  803.238212  8221.012973  0.066814  6.891659  0.328721

         deltaPtc  Number_of_plates
1859719  23.32789               210

[1 rows x 38 columns]
<ipython-input-37-2b68bb861d7a>:69: SettingWithCopyWarning:
A value is trying to be set on a copy of a slice from a DataFrame.
Try using .loc[row_indexer,col_indexer] = value instead

See the caveats in the documentation: https://pandas.pydata.org/pandas-docs/stable/user_guide/indexing.html#returning-a-view-versus-a-copy
  da["Number_of_plates"] = initial_number_of_plates
```

	PORT_SIZE	THICKNESS	PLATE_SPACING	A1	A1p	E_FAC	Dh	Ach	Gch	Reh	...	fc	deltaPch	deltaPcc	Number_of_plates	Gph	Gpc	deltaPph	deltaPpc	deltaPth	deltaPtc
1859719	0.075657	0.00102	0.00495	0.1962	0.153545	1.277798	0.007748	0.002673	12.927431	220.224148	...	0.330265	0.261908	16.436231	210	803.238212	8221.012973	0.066814	6.891659	0.328721	23.32789

1 rows × 38 columns

```
final[final.Q == min(final.Q)].iloc[0]
```

```
PORT_SIZE                0.075657
THICKNESS                 0.00102
PLATE_SPACING             0.00495
A1                         0.1962
A1p                      0.153545
E_FAC                    1.277798
Dh                       0.007748
Ach                      0.002673
Gch                     12.927431
Reh                    220.224148
Chh                           0.3
nh                          0.663
Nuh                     20.458246
hh                    1345.626893
Gcc                    132.310165
Rec                   1275.952598
Chc                           0.3
Nuc                      60.45715
hc                    4816.154736
U                      998.220598
Uf                     994.844147
Q                  1555301.810029
Qf                 1550041.048162
Kph                         18.29
```

```
final[final.Q == min(final.Q)].iloc[0]
```

```
PORT_SIZE                0.075657
THICKNESS                 0.00102
PLATE_SPACING             0.00495
A1                         0.1962
A1p                      0.153545
E_FAC                    1.277798
Dh                       0.007748
Ach                      0.002673
Gch                     12.927431
Reh                    220.224148
Chh                           0.3
nh                          0.663
Nuh                     20.458246
hh                    1345.626893
Gcc                    132.310165
Rec                   1275.952598
Chc                           0.3
Nuc                      60.45715
hc                    4816.154736
U                      998.220598
Uf                     994.844147
Q                  1555301.810029
Qf                 1550041.048162
Kph                         18.29
Kpc                         1.441
mh                          0.652
mc                          0.206
fh                       0.542832
fc                       0.330265
deltaPch                 0.261908
deltaPcc                16.436231
Number_of_plates              210
Gph                    803.238212
Gpc                   8221.012973
deltaPph                 0.066814
deltaPpc                 6.891659
deltaPth                 0.328721
deltaPtc                 23.32789
Name: 1859719, dtype: object
```

4. Conclusion & Discussion

Various trials were conducted with varying port sizes, number of plates, plate thickness, horizontal and vertical plate distance, chevron angle, and enlargement factor to work out the optimum design for the plate-type heat exchanger. The code compared the resulting heat transfer rate from the initials given with the heat transfer rate from the code. The Trial with the minuscule difference in heat transfer rate and pressure drop of less than 25 psi was considered our optimum value. Since we were not given more constraints, we assumed values such as chevron angle and horizontal and vertical plate distance. Several variables were kept constant for simplification and to get our desired result. Since we have 30 weight% acetic acid mixture solution, we used titanium as our material for design and assumed minor roughness. More than 25% acetic acid in a mixture means a non-diluted acetic acid mixture that has harsh corrosive effects on the material; due to that reason, in the future, with a more complex design system, one can also consider picking polymer-coated or thin-film coated heat exchangers to reduce this corrosive effect. Titanium assumption is made solely on the assumptions prior that for nitric acid substance, titanium is valuable therefore; we inductively deduced that it could be helpful to prevent the corrosive effects of the acetic acid in the non-diluted fluid. One can argue that the cost of titanium, since it is an expensive metal, may, in a general engineering design and cost sense, makes it unlikely to be used; however, this might be a luxury royal perfumer that is willing to give any amount of money for the best quality. One should know the context without assuming cost-effectiveness, therefore can neglect the cost of the design and just look at the ideal design patterns.

In the conducted design project, we found the optimal design parameters of a constraint Plate type heat exchanger with one-pass/one-pass design applied Kumar’s correlation and various other approximations such as ideal behavior, C_p due to this behavior considered as ideal and, based on these prior approximations, we found the values that made the optimization problem to start. Without eliminating the non-linearity in the function or not solving the non-linear partial differential function within certain negligible error margins, we deduced an optimal result within the variance. This behavior is commonly used in engineering approximations, as seen from the experimentally found equation, such as the Fokker-Planck equation.

5. Nomenclature

- **T_{hi} =** Hot inlet Temperature [K]
- **T_{ci} =** Cold inlet Temperature [K]
- **T_{co} =** Cold outlet Temperature [K]
- **T_{ho} =** Hot outlet Temperature [K]
- **Re** = Reynolds number [dimensionless]
- **Cp =** Heat capacity in constant pressure for ideal solution [$\frac{W}{m^2 \cdot K}$]
- **Pr =** Prandtl Number [dimensionless]
- **Nu_h** = Nusselt number [for a hot fluid]
- **Nu_c** = Nusselt number [for a cold fluid]
- **G_c** = Mass velocity through a channel [kg/(s.m^2)]
- $\Delta p_c \ = \ channel\, pressure\ drop$ [psi]
- $\Delta p_p \ = \ port\ pressure\ drop$ [psi]
- **t** = thickness [m]
- **P** = Port size [m]
- **A_1** = Single plate effective area[m^2]
- **A_{1p}** = Single plate projected plate area [m^2]
- **D_h** = Hydraulic Diameter [m]
- **LMTD** = Log Mean Temperature Difference [K]

6. References

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