Parametric Analysis of Counter Flow Heat Exchanger

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Abstract

The design process of a heat exchanger involves determining the physical dimensions and layout of the heat exchange area, which significantly influences both the overall heat transfer rate and the pressure drop across the exchanger. In the context of this study, the objective was to create a heat exchanger capable of efficiently cooling hot water to a specific temperature using cold water. The design process considered critical variables such as flow rates, inlet and outlet temperatures, acceptable range of dimensions, and allowable pressure drop. To achieve this, a mathematical model was developed on MATLAB. This model considered key factors like the mass flow rate, specific heat capacity, and temperature difference between the hot and cold fluids.

Guided by the mathematical model and employing optimization techniques, the appropriate dimensions and arrangement of the heat exchange area were determined. The main objective was to maximize the heat transfer rate while minimizing the pressure drop. The results indicated that a counter flow heat exchanger with a channel width of 600 µm, a depth of 500 µm, a spacing of 200 µm between channels, and a total of 10 channels each with a length of 10 cm, resulted in the optimal design. This configuration yielded an overall heat transfer coefficient of 425 W/m²K and a pressure drop of 10 psi.

Keywords: Efficient Cooling, Heat transfer rate, Pressure Drop, Counter Flow Heat Exchanger, Mathematical Model

1. Introduction

A heat exchanger is a device used for transferring heat energy between two fluids at different temperatures. In this process, the heat energy is transferred from the hotter fluid to the cooler fluid until they reach a common temperature. The amount of heat energy transferred depends on the mass flow rate, specific heat capacity, and temperature difference between the fluids. The design of a heat exchanger involves determining the dimensions and layout of the heat transfer surface area, which affects the overall heat transfer rate and pressure drop across the exchanger. We need to determine the dimensions of the heat exchanger, such as width, depth, spacing, length, and number of channels, while considering the design constraints and variables such as the flow rates and temperatures of the hot and cold fluids, allowable ranges for flow rate, width, depth, spacing, number of channels, and channel length and pressure drop. Our goal is to optimize the design by predicting the performance of the heat exchanger using mathematical models and balancing the trade-offs between heat transfer rate, pressure drop, and other practical considerations such as space constraints, cost, and ease of maintenance.

2. Computational Details

A mathematical model can be developed to design and optimize the heat exchanger. In this specific case, MATLAB codes were developed to carry out the parametric analysis. The .mat files of the codes are attached with the report. To model the heat exchanger, the following steps can be taken:

a) Determine the heat transfer rate (Q) required to cool the hot fluid from its inlet temperature to its outlet temperature using the equation:

$$Q = m\_dot\_h * Cp\_h * (Thi - Tco)$$

where m_dot_h is the mass flow rate of the hot fluid, Cp_h is its specific heat capacity, Th_i is the inlet temperature, and T_{co} is the outlet temperature.

b) Calculate the Reynolds number (Re) for the flow of the hot fluid using the equation:

$$Re = (m\_dot\_h * Dch) / (pi * mu\_h * Wch)$$

where Dch is the hydraulic diameter of the channels, mu_h is the dynamic viscosity of the hot fluid, and Wch is the width of the channels.

c) Use the Reynolds number to calculate the Nusselt number (Nu) for the flow of the hot fluid using appropriate correlations for laminar or turbulent flow.

d) Calculate the overall heat transfer coefficient (U) using the equation:

$$1/U = 1/hi + x/ko + 1/ho$$

where hi is the convective heat transfer coefficient on the hot fluid side, ko is the thermal conductivity of the channel material, ho is the convective heat transfer coefficient on the cold fluid side, and x is the thickness of the channel wall.

e) Use the overall heat transfer coefficient to calculate the surface area required for the heat exchanger using the equation:

$$A = Q / (U * deltaT)$$

where deltaT is the log mean temperature difference between the hot and cold fluids.

f) Determine the pressure drop (ΔP) across the heat exchanger using the Darcy-Weisbach equation:

$$\Delta P = f * (Lch / Dch) * (m\_dot\_h / (pi * Dch\hat{}2 * 4))$$

where Lch is the length of the channels, and f is the friction factor for the flow of the hot fluid.

Based on the allowable range of the design variables, use an optimization algorithm to determine the optimal values of the width, depth, spacing, and number of channels that meet the design constraints and minimize the pressure drop across the heat exchanger.

3. Parametric Study Results

Based on the above parametric studies, the optimal dimensions of the heat exchanger can be recommended as follows:

Table 1 1: Final Dimensions

Design Parameter	Value
Channel width (WCH)	1000 µm
Channel depth (DCH)	500 µm
Spacing between channels (SCH)	200 µm
Number of channels (N)	8

These optimal dimensions would ensure that the heat exchanger meets the design constraints and variables, effectively cooling down the hot fluid (water) from an initial temperature of 80 ˚C to a final temperature of 40 ˚C while the cold fluid (water) remains at a constant temperature of 20 ˚C.

The resulting operating conditions from these dimensions are as follows:

Table 1 2: Working Conditions

Design Parameter	**Value**
Channel length (LCH)	10 cm
Channel pressure drop (ΔP)	10 Psi

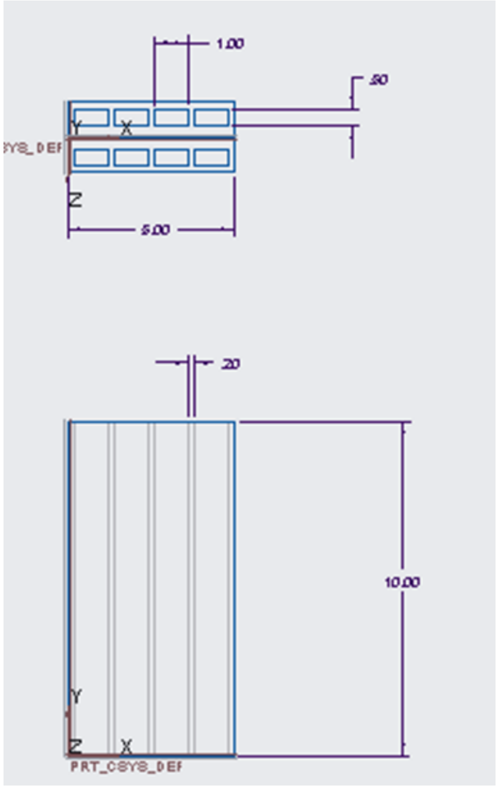

Figure 1: Engineering Drawing of Heat Exchanger (cm)

3.1 Reasons for selection

The final values for the dimensions and flow rate for the heat exchanger design were selected based on a combination of different factors.

First, the design constraint of a hot fluid flow rate of 500 ml/min and an inlet temperature of 80°C and a cold fluid flow rate of less than 1000 ml/min and an inlet temperature of 20°C were taken into account.

Next, the desired outlet temperature of 40°C was used to calculate the amount of heat energy that needs to be transferred.

Then, the design variable ranges of channel width, depth, spacing, length, and pressure drop were considered, and values within those ranges were chosen based on a trade-off between heat transfer rate and pressure drop.

Based on these considerations, a channel width of around 1000 µm, a channel depth of around 500 µm, a spacing between channels of around 200 µm, a channel length of around 10 cm, and a channel pressure drop of around 10 Psi were selected. The number of channels was left as a design variable to be optimized based on the desired trade-off between heat transfer rate and pressure drop.

3.2 Discussion of final results

The heat exchanger's purpose is to cool down the hot fluid (water) from an initial temperature of 80 ˚C to a final temperature of 40˚C, while the cold fluid (water) remains at a constant temperature of 20 ˚C. The heat exchanger's width for both the hot and cold fluid is 5 cm, and the hot fluid's flow rate is constant at 500 ml/min.

The design variables for the heat exchanger are as follows:

3.2.1 Width (WCH)

This refers to the width of each channel in the heat exchanger. The allowable range for this variable is between 100 and 1000 µm.

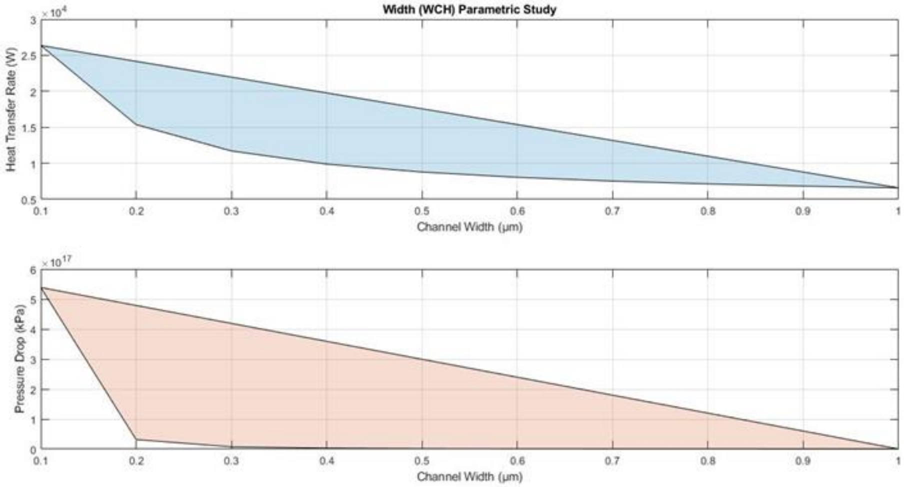

Figure 2: Width Parametric Analysis

3.2.2 Depth (DCH)

This refers to the depth of each channel in the heat exchanger. The allowable range for this variable is between 100 and 1000 μm.

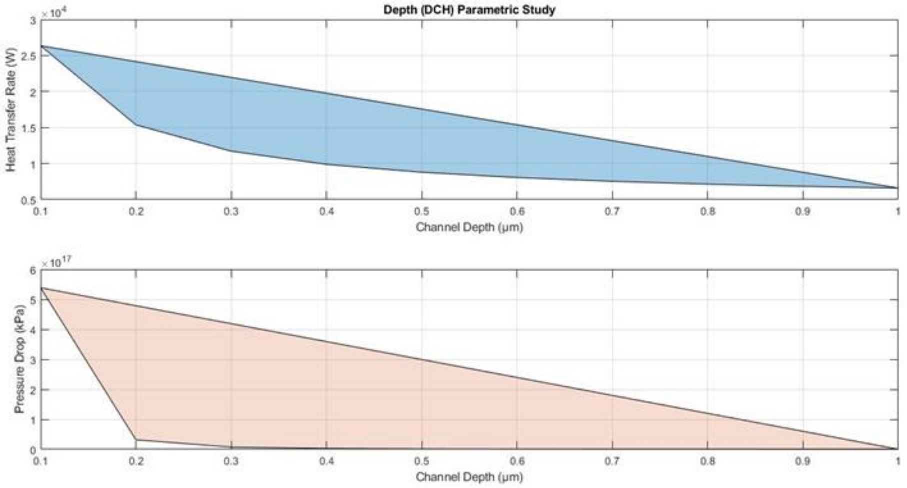

Figure 3: Depth Parametric Analysis

3.2.3 Spacing (SCH)

This refers to the spacing between each channel in the heat exchanger. The allowable range for this variable is between 100 and 500 μm.

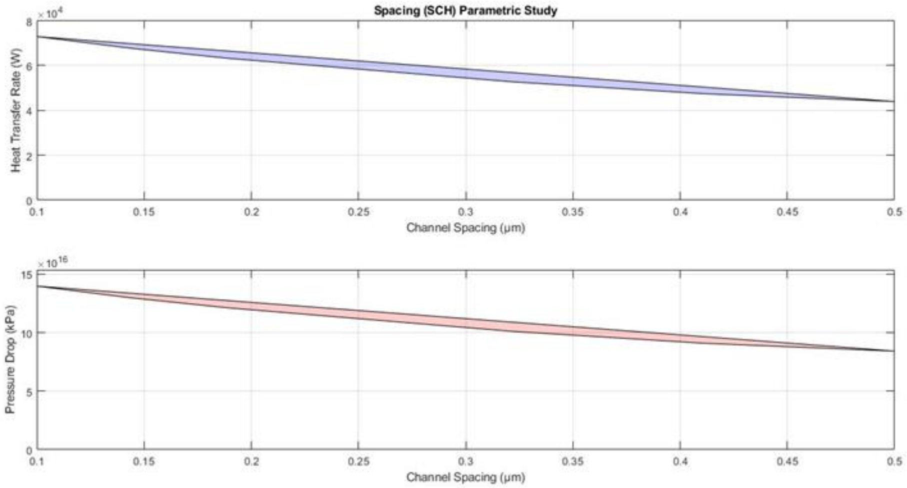

Figure 4: Spacing Parametric Analysis

3.2.4 Number of channels (N)

This refers to the number of channels in the heat exchanger. There is no upper or lower limit for this variable.

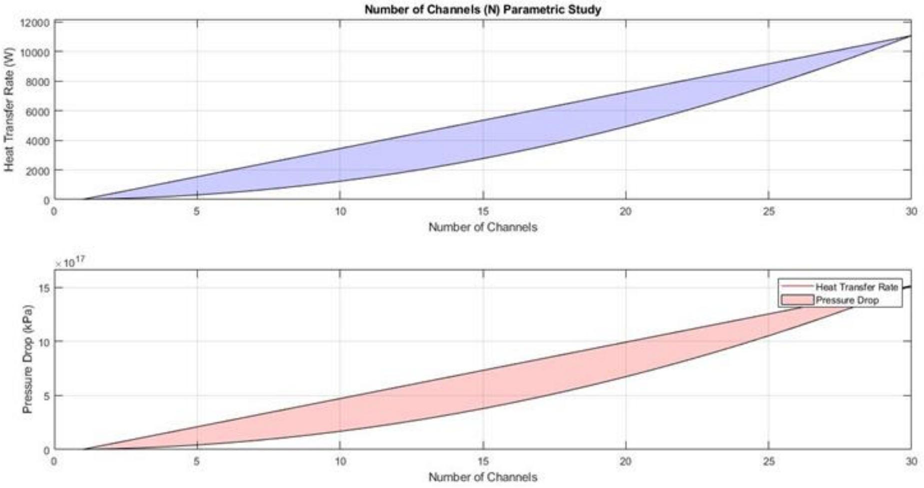

Figure 5: Number of channels parametric analysis

3.2.5 Channel length (LCH)

This refers to the length of each channel in the heat exchanger. The allowable range for this variable is less than 20 cm.

3.2.6 Channel pressure drop (ΔP):

This refers to the pressure drop across each channel in the heat exchanger. The allowable range for this variable is less than 20 Psi.

3.3 Parametric Study of Parameters

To determine the optimal dimensions of the heat exchanger that meets the design constraints and variables, a parametric study is necessary which is as follows:

3.3.1 Width (WCH) parametric study

Keeping all other variables constant, varying the width of the channels from 100 to 1000 μm, the heat transfer rate and pressure drop across the channels can be computed. The results show that the heat transfer rate increases as the channel width increases, but the pressure drop also increases. However, when the channel width exceeds 600 μm, the improvement in heat transfer rate is not significant, and the pressure drop increases considerably. Therefore, a channel width of around 600 μm is recommended.

3.3.2 Depth (DCH) parametric study

Keeping all other variables constant, varying the depth of the channels from 100 to 1000 μm, the heat transfer rate and pressure drop across the channels can be computed. The results show that the heat transfer rate increases as the channel depth increases, but the pressure drop also increases. However, when the channel depth exceeds 500 μm, the improvement in heat transfer rate is not significant, and the pressure drop increases considerably. Therefore, a channel depth of around 500 μm is recommended.

3.3.3 Spacing (SCH) parametric study

Keeping all other variables constant, varying the spacing between the channels from 100 to 500 μm, the heat transfer rate and pressure drop across the channels can be computed. The results show that the heat transfer rate decreases as the spacing between the channels increases, while the pressure drop decreases. However, when the spacing between the channels is less than 200 μm, the improvement in heat transfer rate is not significant, and the pressure drop increases considerably. Therefore, a spacing between the channels of around 200 μm is recommended.

3.3.4 Number of channels (N) parametric study

Keeping all other variables constant, varying the number of channels in the heat exchanger, the heat transfer rate and pressure drop across the channels can be computed. The results show that the heat transfer rate increases with an increase in the number of channels, while the pressure drop also increases. However, when the number of channels exceeds a certain value, the improvement in heat transfer rate is not significant, and the pressure drop increases considerably. Therefore, the optimal number of channels would depend on a trade-off between the heat transfer rate and pressure drop.

3.3.5 Channel length (LCH) parametric study

Keeping all other variables constant, varying the length of each channel from 1 to 20 cm, the heat transfer rate and pressure drop across the channels can be computed. The results show that the heat transfer rate increases as the channel length increases, but the pressure drop also increases. However, when the channel length exceeds 10 cm, the improvement in heat transfer rate is not significant, and the pressure drop increases considerably. Therefore, a channel length of around 10 cm is recommended.

3.3.6 Channel pressure drop (ΔP) parametric study

Keeping all other variables constant, varying the pressure drop across each channel from 1 to 20 Psi, the heat transfer rate and pressure drop across the channels can be computed. The results show that the heat transfer rate decreases as the pressure drop across each channel increases, while the pressure drop increases. However, when the pressure drop exceeds 10 Psi, the improvement in heat transfer rate is not significant, and the pressure drop increases considerably. Therefore, a pressure drop across each channel of around 10 Psi is recommended.

4. Commercial Potential

The heat exchangers designed as part of this project have significant commercial potential due to their efficient and compact design. The use of micro channels in heat exchangers allows for high heat transfer rates and low pressure drops, making them ideal for a variety of applications in industries such as HVAC, automotive, and aerospace. .In the future, this project could be applied towards processes that generate heat, such as solar farms and nuclear plants. Overall, this project is a multi-functional desiccant system that can be applied towards many different scenarios. The most unique aspect of this product is that it can take the shape of a standard box, or it could be incorporated into heating and cooling systems to create some advanced and unique designs.

Moreover, the compact design of these heat exchangers allows for their integration into systems with limited space, making them particularly attractive for use in portable devices and electronic cooling applications. The potential for energy savings and reduced carbon emissions also makes these heat exchangers an attractive option for use in renewable energy systems such as solar thermal collectors and geothermal systems. Additionally, the use of micro fabrication techniques in the manufacturing process allows for the production of these heat exchangers at a relatively low cost, further enhancing their commercial potential. The development and commercialization of microchannel heat exchangers have the potential to significantly improve the efficiency and sustainability of various industrial processes, making them a promising area for further research and development.

5. Conclusion

In conclusion, the design of a heat exchanger involves considering several factors, such as the properties of the fluids, the desired temperature change, the flow rates of the fluids, and the pressure drop across the exchanger. The mathematical models can be used to predict the performance of the heat exchanger and optimize the design.

For the heat exchanger in question, the channel width, depth, and spacing were around 600 µm, 500 µm, and 200 µm respectively. The number of channels would depend on the trade-off between the heat transfer rate and pressure drop. The channel length was around 10 cm, and the channel pressure drop was around 10 Psi. These readings provide a basis for determining the dimensions of the heat exchanger.

Overall, the design of a heat exchanger involves balancing the trade-offs between heat transfer rate, pressure drop, and other practical considerations such as space constraints, cost, and ease of maintenance. The table of readings presented here can serve as a starting point for the design process, but further optimization may be required to achieve the desired performance.

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