Multiphysics Simulation of a Printed Circuit Heat Exchanger

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Abstract: Compact Heat Exchangers, specifically Printed Circuit Heat Exchangers, are widely used in industry as a replacement for traditionally large heat exchangers (e.g. Shell and Tube) due to their small size and high effectiveness. Modelling of PCHEs, specifically those manufactured by Heatric has proven to be difficult due to the limited internal design information provided by the manufacturer. The current work is focused on developing a computational model of a Heatric PCHE using COMSOL for direct comparison to the results of an ANSYS model of an identical PCHE found in the literature. The present results show a percentage difference between the two models for the outlet temperatures of approximately 1.6% and 2.4% for the hot and cold channels respectively. The corresponding pressure drop is approximately 0.15% which is comparable to the 0.13% pressure drop found in the previous study.

Keywords: Heat Transfer, PCHE, Heatric, Laminar Flow.

1. Introduction

Compact Heat Exchangers are a class of heat exchanger that incorporates a large amount of heat transfer area per unit volume. As the name suggests, they are much smaller than traditional, such as those of the shell and tube variety. Their primary advantage is a higher efficiency and therefore they do not consume much space and are more efficient. One type of compact heat exchanger is the Printed Circuit Heat Exchanger (PCHE).

PCHEs are made through chemically etching semicircular channels onto a steel plate for fluid passage. Tens of plates are then stacked on top of each other, diffusion bonded into a monolithic structure, and enveloped in a casing.

Heatric, a heat exchanger manufacturing company based in the United Kingdom, is a key manufacturer PCHEs. However, due to confidentiality policies, information related to the internal geometry and channel arrangements are not disclosed. For this reason, modelling of these PCHEs has proven to be difficult. Several researchers have estimated internal geometries of the PCHEs in order to model their heat exchange characteristics. Moisseyetsev et. al, developed a method to determine the zig zag angles of the flow channels and their relation to pressure loss [1]. Pieve, described several methods that can be used to size the channels of the heat exchanger [2]. These techniques simplify efforts to properly model the thermal behavior of the fluid in the heat exchanger.

Numerous researchers have developed models of Heatric PCHEs. Figley, developed an ANSYS model for a Heatric PCHE with Helium as the working fluid [3]. In the present study, a COMSOL model based on the work of Figley has been constructed and simulated and temperature and pressure variations for both models have been compared.

2. Model Description

The PCHE is made up of semicircular channels etched onto steel that are subsequently stacked and bonded. In a PCHE, the flow moves in a purely counter flow arrangement with the exception of the inlets and outlets where they move in a cross flow arrangement. Given that the bulk of the PCHE is counter flow, the cross flow area is neglected in the model. Figley analyzed a simplified geometric model of the PCHE involving 20 plates stacked vertically (10 hot channels and 10 cold channels) where each plate contained only 1 semicircular channel for fluid flow [3]. The model dimensions used by Figley are available in Table 1.

This model was recreated in COMSOL where only half the model was simulated to reduce computational time. The present model is shown in Figures 1 and 2 in different orientations. The semicircular domains in the model are the fluid domain with Helium used as the working fluid. The remaining parts are the solid domain and are modelled as AISI 4240 Steel.

Table 1: Model Dimensions

Number of Hot Plates	10
Number of Cold Plates	10
Plate Thickness (mm)	1.6
Plate Width (mm)	3.6
Total Plate Height (mm)	32.9
Plate Length (mm)	247.2
Number of Channels per plate	1
Channel Diameter (mm)	2
Channel Length (mm)	247.2

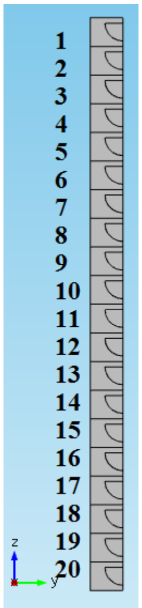

Figure 1. Front view of PCHE COMSOL model

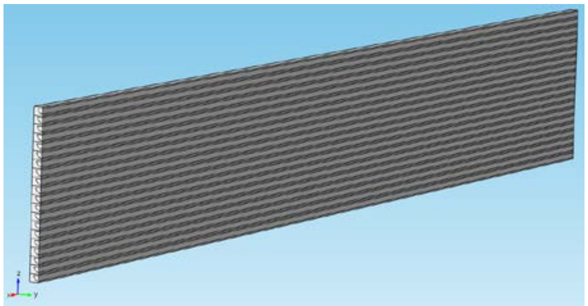

Figure 2. Symmetric view of COMSOL model

3. Governing Equations and Boundary Conditions

Before analyzing the model, it is important to highlight the governing equations that were used to model the fluid. For the solid domain, the governing equation is conservation of energy to model the conduction within the wall. The fluid flow was found to be laminar within the semicircular channels, and the mathematical model includes conservation of energy, conservation of mass and conservation of momentum for the fluid domains.

Conservation of Energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$$

Conservation of Mass:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=0$$

Conservation of Momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial z}$$

As seen in Figures 1 and 2, the channel symmetry within the PCHE was used to reduce the computation domain. A symmetry boundary condition was applied at the mid-plane. The remaining boundary conditions applied to this model are shown in Table 2.

Table 2: Boundary conditions

Laminar Flow Physics		
Hot Inlet Boundary Condition	Pressure	3 MPa
Cold Inlet Boundary Condition	Pressure	3 MPa
Hot Outlet Boundary Condition	Mass Flow Rate	0.75 kg/h
Cold Outlet Boundary Condition	Mass Flow Rate	0.75 kg/h
Heat Transfer Physics		
Hot Inlet Temperature	1173 K	
Cold Inlet Temperature	813 K	
Outflow	Both Cold and Hot outlets	

4. Grid Sensitivity Analysis

A grid sensitivity analysis was performed on the number of elements in order to determine convergence of the mesh. The results of this effort are shown in Figure 3. The convergence study focused on the temperature variation within the hot channel as it is losing heat to the cold channel and therefore decreasing in temperature. The results indicate that the steady state solution converges when using 315,400 elements, with a variation of less than 0.1%. Any increase in the number of elements beyond this value had a negligible effect on the results.

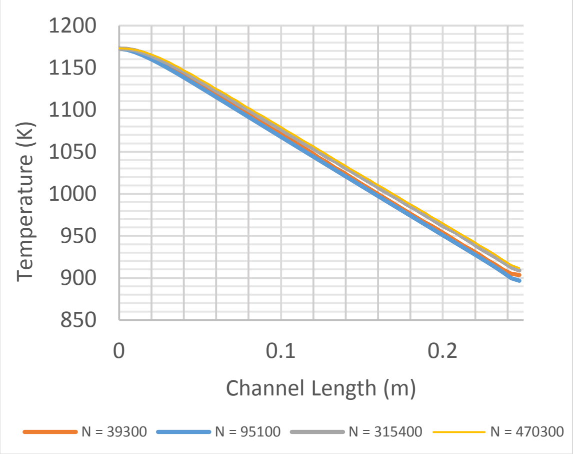

Figure 3. Grid sensitivity analysis

5. Results

A stationary study was run to obtain the steady state solution for the heat exchange within the model. Channels numbers 10 and 11 were monitored as they are central channels within the heat exchanger. These results are represented by the temperature and pressure variations that are plotted (Figures 4, 5 and 7) and discussed.

5.1 Temperature

As seen in Figure 4, Helium enters the top channel (number 10) uniformly at a temperature of 1173 K and loses heat to its upper and lower boundaries (channels 9 and 11). Similarly, Helium enters the bottom channel uniformly at a temperature of 813 K and gains the heat from its boundaries (channels 10 and 12). Both channels are shown isometrically to emphasize their axial temperature variation and gradients. Both channels show a linear temperature change, which is highlighted in Figure 6.

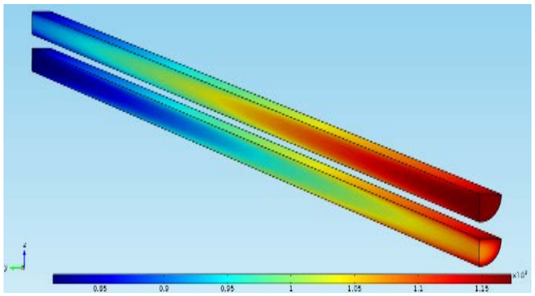

Figure 4. Temperature gradient of hot channel 10 (top) and cold channel 11 (bottom)

The steel walls act as an intermediary to regulate the heat exchange. Although there is heat being exchanged between the fluids, there is also an aspect of axial conduction within the steel which exists due to the temperature gradients. Figure 5 shows the variation in temperature of both the fluids and the walls surrounding channels 10 and 11. As expected, the temperature gradient along the walls is much steeper than the gradients within the Helium due to this axial conduction.

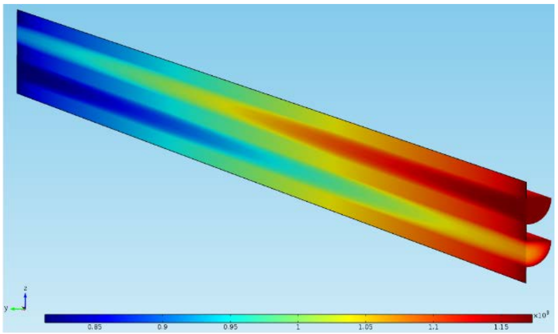

Figure 5. Temperature gradient of hot channel 10 (top) and cold channel 11 (bottom) and surrounding walls

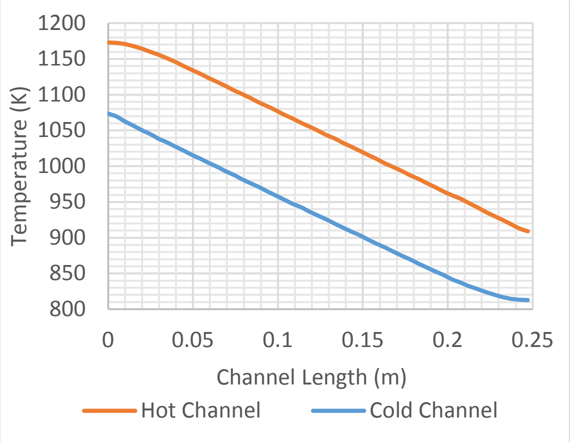

Figure 6. Centerline temperatures of channels 10 and 11

The centerline temperatures of both channels varying along their length are plotted in Figure 6. As we observe from Figure 6, the temperature changes are mostly linear and consistent with the exception of the inlet of both channels. The variations in the entry region are related to the development of the thermal boundary layer within the channels. The thermal boundary later appears to fully develop at a distance of approximately 20 mm into each channel, after which the temperature gradient in the channel becomes linear. The temperature of the flow in the hot channel decreases from the initialized value of 1173 K to reach a temperature of 910 K at the outlet, whereas the temperature of the flow in the cold channel increases from the initialized temperature 913 K to reach an outlet temperature of 1073 K.

5.2 Pressure

Figure 7 shows the pressure drop across the channels. As expected, due to the identical channels walls surrounding both fluid streams (steel), the pressure drop is approximately equal in both channels with only slight differences noticeable. The centerline pressure drop of both channels were plotted and are shown in Figure 8.

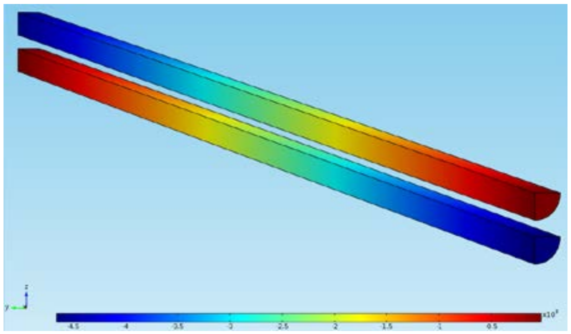

Figure 7. Pressure gradient of hot channel 10 (top) and cold channel 11 (bottom)

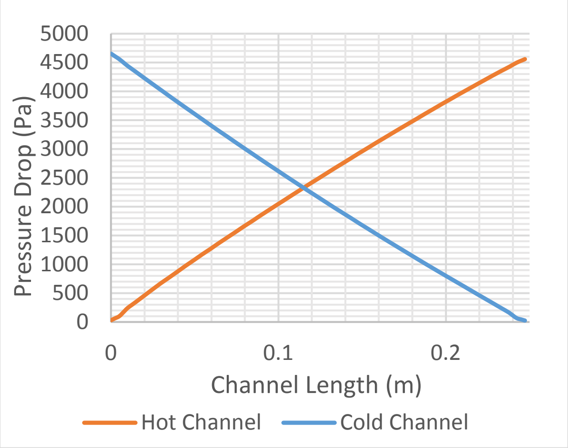

Figure 8. Centerline pressure drops of channels 10 and 11

Figure 8 shows that the pressure loss in the hot channel was found to be 4.56 kPa, which is equivalent to a 0.15% drop from the original 3 MPa inlet pressure. The pressure loss in the cold channel was found to be 4.65 kPa which is similarly a 0.15% drop from the 3 MPa

5.3 Comparisons

The above results were compared with the results obtained and published from the ANSYS model [3]. Direct comparisons between the present study and the work of Figley are found in Table 3.

Table 3: COMSOL and ANSYS Comparisons

Temperature			
	ANSYS	**COMSOL**	**%Difference**
Hot Outlet	895 K	910 K	1.6%
Cold Outlet	1100 K	1073 K	2.4%
Pressure Drop			
	ANSYS	**COMSOL**	**%Difference**
Hot Channel	3863 Pa	4560 Pa	18.0%
Cold Channel	3678 Pa	4652 Pa	26.5%

A quick analysis of the temperature variations reported by Figley [3] demonstrates that the development of the thermal boundary layer was not reported. For a direct comparison of the results from the present study to those of Figley, the effect of the thermal boundary layer development must be considered. If we account for the differences caused by this region of the simulation, the results generated by COMSOL in the present study represent a percent difference of 0.2% from those of Figley.

As for the pressure differences, even though percent difference of 18% and 26.5% between the two models may seem large, representing them with respect to the pressure shows they are fairly small. A comparison of the percentage of the pressure loss shows a 0.13% pressure drop from the ANSYS model and 0.15% pressure drop from the COMSOL model. This difference is most probably due to the roughness inherent in the choice of material for the type of steel used in the calculations of the model.

6. Conclusions

We were able to successfully implement a heat transfer model of a PCHE within COMSOL to analyze the temperature and pressure profiles within a heat exchanger. The temperature distributions and pressure losses were close to the expected response found in a PCHE. A comparison to previous efforts by Figley using an ANSYS model [3]; demonstrated similar results with percent differences for the temperature of 1.6% and 2.4% for the hot and cold channels, respectively. The pressure percentage drop calculated by Figley was found to be 0.13% whereas the pressure percentage drop calculated using COMSOL was found to be 0.15%. These results increased our confidence in the capabilities of COMSOL for modelling PCHEs. Future work will use experimental results to validate these models.

7. References

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