2018

Heat Transfer Enhancement Using Approximation Assisted Optimization for Pillow Plate Heat Exchangers

Radia Eldeeb
University of Maryland, College Park, United States of America, radiame@umd.edu

Jiazhen Ling
University of Maryland, College Park, United States of America, jiazhen@umd.edu

Vikrant Chandramohan Aute
University of Maryland College Park, vikrant@umd.edu

Reinhard Radermacher
CEEE, University of Maryland, United States of America, raderm@umd.edu

Heat Transfer Enhancement Using Approximation Assisted Optimization for Pillow Plate Heat Exchangers

Radia ELDEEB[1], Jiazhen Ling[2], Vikrant AUTE[3]*, Reinhard RADERMACHER[4]

Center for Environmental Energy Engineering,
Department of Mechanical Engineering, University of Maryland
College Park, MD 20742, USA

[1]Tel: 301-405-7314, [2]Tel: 301-405-8672, [3]Tel: 301-405-8726, [4]Tel: 301-405-5286

[1]Email: radiame@umd.edu, [2]Email: jiazhen@umd.edu, [4]Email: raderm@umd.edu

* Corresponding Author Email: vikrant@umd.edu

ABSTRACT

Optimization is a powerful mathematical methodology that can be employed to miniaturize and improve the performance of plate heat exchangers in order to achieve higher compactness and energy efficiency. Achieving these goals means less material used, and less charge, and thus a lower impact on the environment. Plate heat exchangers (PHXs) are favored by the HVAC&R industry since they are compact, and they have desirable thermal-hydraulic characteristics due to their small approach temperature. However, the challenge with plate heat exchangers lies with the cost of new designs. Pillow plate heat exchanger (PPHX) is a promising type of PHXs which also possesses desirable thermal-hydraulic characteristics due to their complex 3D wavy structure which creates a fully developed turbulent flow enhancing heat transfer. Furthermore, PPHXs are manufactured in a simpler more economical way compared to conventional PHXs. In this study, novel PPHXs designs are investigated in order to maximize the thermal-hydraulic performance. The PPHX pillow surface is created using CFD simulations ensuring structural stability while resembling the manufacturing process. The computational domain is then obtained from the deformed surface, meshed, and simulated. The whole CFD simulation process with its different components is automated using a Python script. The optimization problem has four design variables which are the spot weld ratio, the spot weld diameter, the pillow height, and the inlet velocity. The objective is to maximize the heat transfer coefficient and minimize the pressure drop per unit length. The potential enhancement is found to be up to 3 times improvement in heat transfer coefficient and up to 98% reduction in pressure drop as compared to a selected PPHX baseline design. Sensitivity analysis is conducted on the optimal designs to provide insights into factors affecting their performance. The sensitivity study shows that the spot weld diameter is a significant parameter where further improvements can be applied.

1. INTRODUCTION

Pillow plate heat exchanger (PPHX) has a complex wavy structure which creates a flow channel with a fully developed turbulent flow. While the manufacturing of some types of PHX designs might require a special die for each new design, the manufacturing process of PPHXs on the other hand is simpler and more economical. Additionally, they have favorable high structural stability, a sealed construction since it is fully welded, and more design flexibility since the geometry of the pillow plate can be varied easily using similar equipment. All these make PPHXs excellent candidates for optimization and further miniaturization in order to reduce the material and refrigerant charge required for the same thermal-hydraulic performance. This can be achieved by optimizing the performance of PPHXs using approximation techniques since it is computationally very expensive to numerically simulate the 3D volume of PHXs. The manufacturing process of PPHXs consists of two thin metal sheets welded together using a certain pattern of spot welding that can be in-line or staggered. The two sheets are then sealed at the edges using seam welding. The plates are then inflated in a hydroforming process creating a pillow shape. The inflated plates are finally stacked together to form the channels of the PPHX. The weld pattern, longitudinal and transverse pitches between the welds, weld shape and size, plate thickness, and pillow height are all geometric factors altering the thermal-hydraulic performance of the PPHX.

PPHXs are commonly used in chemical and process industry in single-phase and two-phase applications. However, research on the utilization of PPHXs in HVAC&R applications is limited. Mitrovic and Peterson (2007) claim to be the first to study what they call a thermoplate. A thermoplate goes through the same manufacturing process as a pillow plate, and possesses very similar geometrical characteristics. They experimented with single phase and two-phase condensation heat transfer and pressure drop using isopropanol as the working fluid. Using their experimental results, they developed heat transfer coefficient and pressure drop correlations. However, they noted in their study that the correlations developed are only valid for isopropanol for the range of parameters specific to their experiments. Mitrovic and Maletic (2011) later performed numerical simulations on thermoplates as well using CFD with water as the working fluid. The Reynolds number investigated ranged from 50-3800 for which they proposed a heat transfer coefficient correlation. The CFD simulations used a laminar flow model although the Reynolds range covered part of the turbulent region which led to the underestimation of the heat transfer rate and pressure drop compared to their experimental results. They also used an approximation for the pillow plate surface geometry using a three-dimensional trigonometric function to describe the wavy surface which resulted in significant inaccuracies as mentioned by Piper et al. (2015).

Piper et al. (2015) used another approach based on numerical forming simulations to determine the geometric characteristics of PPHXs. The approach developed is described as flexible, and it well predicts the actual hydroforming process of manufacturing PPHXs. They developed correlations to calculate the pillow plate channel volumetric mean hydraulic diameter, wetted heat transfer area, channel cross-section area, and channel volume. However, the correlations are developed based on a limited number of geometries which might have caused some inaccuracies in the model developed (Eldeeb et al., 2016). The correlations developed, however, can be very useful as an initial attempt to calculate PPHXs geometric parameters but, as mentioned in their work, more accurate design methods must be developed for detailed design of PPHX surfaces in order to minimize the design uncertainty. Piper et al. (2016) performed a CFD study using a turbulent single-phase water flow in PPHXs with Reynolds number ranging from 1000-8000. In their study, the PPHX surface is obtained using forming simulations as well. In order to define the thermal-hydraulic performance of the PPHX, they defined an efficiency based on the total heat transfer divided by the total pumping power required. By comparing this defined efficiency, they concluded that a lower Reynolds number, larger pillow height, and transverse weld pattern result in better performance. They also concluded that a smaller weld diameter and an oval weld shape can significantly reduce the pumping power leading to a higher efficiency, although the heat transfer area is reduced as well.

Piper et al. (2017) later used these simulations to develop and verify heat transfer coefficient and pressure drop correlations. The correlations developed agree with their numerical simulations within ±15% and cover a wide range Prandtl number of 1-150. The correlations, however, do not capture lower Reynolds numbers, neglect the effect of the pillow height, which yet needs to be validated in their future work, and are developed using a limited number of plate geometries. In order to obtain a more accurate correlation, more geometries might need to be investigated to cover a greater range of geometric parameters as well as Reynolds number and more validation might be required as well. Finally, another study by Tran et al. (2017) shows that the heat transfer coefficient values in PPHXs are higher as compared to vertical tubes in coupled condensation-evaporation applications. In this paper, the optimization of PPHXs thermal-hydraulic performance is investigated. The PPHX geometry is studied using a commercially available CFD package, and Parallel Parameterized CFD (PPCFD). The optimization is carried out using a Multi-Objective Genetic Algorithm (MOGA) (Deb, 2011). It is desired to bring the thermal-hydraulic and economic advantages of PPHX into the spotlight in HVAC&R with optimized geometry which can give it a strong competitive advantage. The optimization of the basic PPHX geometry with spot welds, can make PPHX a competitive design, not solely among PHXs, but even among others types of compact heat exchangers as well.

2. METHODOLOGY

The current work is based on the optimization method introduced by Abdelaziz et al. (2010). The method introduced consists of employing Approximation Assisted Optimization (AAO) using Parallel Parameterized CFD (PPCFD) (Abdelaziz et al., 2010) using Kriging metamodeling (Cressie, 1993), and Multi-Objective Genetic Algorithm

(MOGA). The optimization procedure is shown in Figure 1. The PPCFD method consists of a code that automatically reads the Design of Experiment (DoE) input parameters and creates journal files for geometry, mesh, and CFD problem settings. An executable batch file is created to sequentially execute the simulations for the entire DoE. In the current work, Latin Hypercube Sampling (LHS) (McKay et al., 1979) is used. The CFD output is then finally processed to get the results for thermal-hydraulic performance. However, automation comes with challenges as the number of components in a system increase as well as the geometry complexity. But generally, if automation is achieved, more than 90% of engineering computational time can be saved using this automation technique (Abdelaziz et al., 2010).

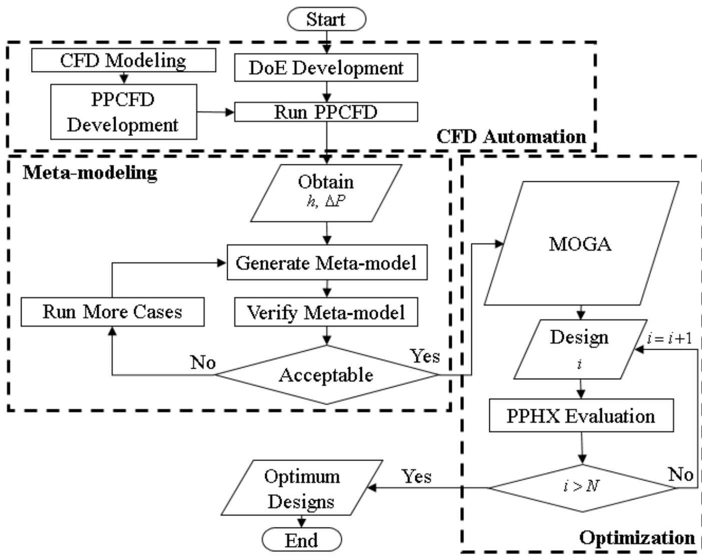

Figure 1: Flow diagram of optimization procedure.

Metamodels are essentially computationally inexpensive simplified models that are capable of capturing the behavior of the underlying system as a function of the independent variables. The metamodel uses a limited number of CFD simulations based on a finite set of parameterized initial designs in a DoE space. The developed metamodel can accurately predict the outcome of CFD simulation for any given design within the design space. This is crucial for many optimization problems in general, and for PPHX in specific as its complex 3D pillow geometry poses a significant challenge in modeling and is very computationally expensive to run. In order to verify the accuracy of the metamodel, it is required to evaluate the ability of the metamodel to accurately predict responses from randomly CFD simulated designs. The acceptability of the metamodel can be established using the Metamodel Acceptability Score (MAS) (Hamad, 2006) which indicates the fraction of predicted responses by the metamodel in which the absolute relative error is equal to or less than an established threshold. The threshold is 10% in the current work.

3. DESIGN

The pillow surface in this study is attained by simulating two thin metal plates made of stainless steel of material EN-1.4541 (AISI 321), bonded together at the welding spots, and undergoing a hydroforming process in ANSYS Static Structural (SS) component (ANSYS Inc., 2016). Figure 2 shows a portion of the pillow surface that results from this process. Staggered circular welds are used in this work. The design space has four design parameters shown with their upper and lower bounds in Table 1. The plate thickness is not a design parameter and is fixed at a value of 0.15 mm. The plate length is fixed at a value of 72 mm.

Although numerical simulations have some drawbacks as an accurate reliable design method for PPHXs, they can also have several advantages. First, the resemblance of the actual manufacturing process gives an acceptable initial prediction of the geometry as compared to other methods such as using trigonometric functions or obtaining coordinates using numerical methods which poorly describes the complex 3D pillow surface. Second, it allows for stress and strain analysis and shows if the maximum strain, necking or fracture is reached at any part of the pillow plate especially at the welding spots. The area surrounding the welding spot is the most vulnerable to failure even before attaining the maximum stress due to the necking of the metal sheet as shown by Piper et al. (2015). Thus, numerical simulation can act as an initial failure test and give a very informative initial insight of the design of the PPHX. However, on must be careful as many uncertainties are embedded and more reliable prediction methods are highly desired and experimental validation is highly required as well.

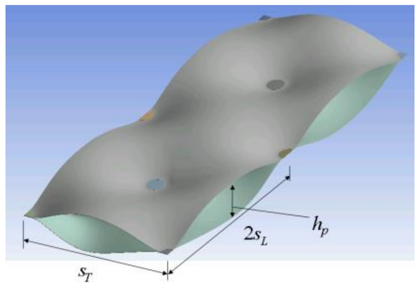

Figure 2: Pillow plate parameters.

Table 1: Design space.

Design Variable	Unit	Lower Bound	Upper Bound
Ratio of transverse pitch and longitudinal pitch $\left({s_T}/{2s_L} \right)$	dimensionless	0.58	1.73
Spot weld diameter $\left(d_{sp} \right)$	mm	3.0	10.0
Pillow height $\left(h_p \right)$	mm	3.0	12.0
Inlet velocity $\left(v_{in} \right)$	m/s	0.1	2.0

4. NUMERICAL MODELING

Single phase, incompressible, turbulent, steady-state water flow is studied. The CFD simulations are performed using ANSYS Fluent (ANSYS Inc., 2016), which is based on finite volume method. The 3D computational domain is shown in Figure 3 consisting of five segments of the basic periodic symmetrical cell of the pillow surface in order to capture both the entrance region as well as the steady state region. A homogeneous inlet velocity, constant outlet atmospheric pressure (0.0 Pa gauge), and symmetrical pillow sides are assumed. A no-slip boundary condition and constant wall temperature are applied. The Reynolds number in this study is defined using

$$Re = \frac{u d_h}{\nu}, \ where \ d_h = \frac{4V}{A_w} \tag{1}$$

The heat transfer coefficient is calculated using the logarithmic mean temperature difference (LMTD) method using

$$h = \frac{Q}{A_{w,i} LMTD} \tag{2}$$

The friction factor is calculated using

$$f = \frac{d_h}{2\rho u^2}\left(\frac{\Delta P}{L} \right) \tag{3}$$

Table 2: Baseline geometric parameters (2016).

Case	$s_T / 2s_L$ (-)	h_i (mm)	d_{sp} (mm)	d_h (mm)
Baseline	0.58	3.0	10	4.1

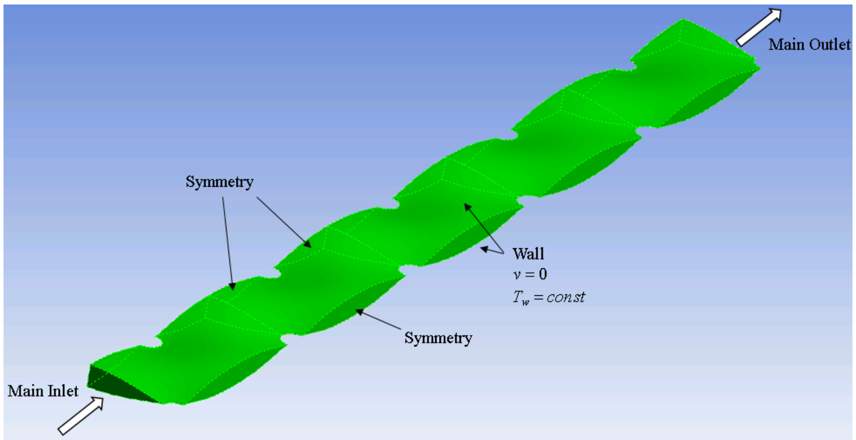

Figure 3: Computational domain.

The baseline case corresponding to one of the geometries studied in Piper et al. (2016) is shown in Table 2. The inlet temperature is 295 K and the wall temperature is 300 K. The pressure-velocity coupling scheme used in the SIMPLEC solver available in ANSYS FLUENT® (ANSYS Inc., 2016). All space discretization schemes are second order degree upwind. This is done to obtain good accuracy with relatively low computational cost, as the 3D CFD simulations of PPHX plates are very computationally expensive. Grid Convergence Index (GCI) (Roache, 1998) method is used for the verification of the CFD models using meshes with different mesh refinement sizes. Three grid resolutions for each case are studied. The GCI analysis results is shown in Figure 4.

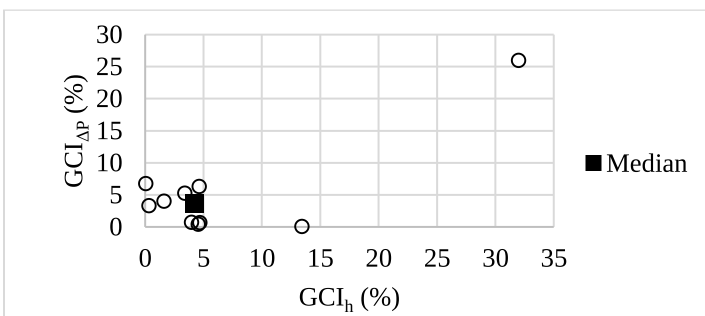

Figure 4: CFD GCI Analysis for PPHX.

The first step in the optimization procedure is to automate the CFD simulations. This is done through writing a Python script which executes the main workbench in ANSYS and calls JavaScript for each part in every component. For each single simulation/design, one python script, and four JavaScript are written. Figure 5 shows the three main components of a single PPHX CFD simulation in ANSYS which are the Static Structural (SS), the Finite Element Modeler (FEM), and the Fluid Flow (FF) components. The PPCFD code and all scripts are written using an external C# code which also writes an executable batch file to run the simulations. Post processing data from CFD simulations is also executed using an external C# code.

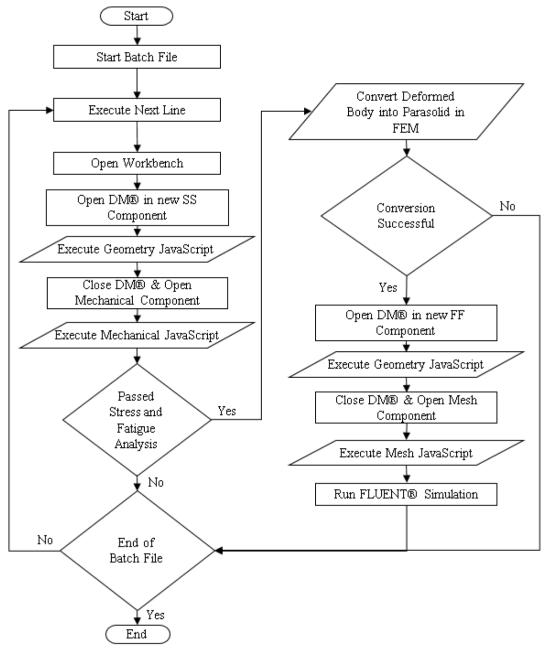

Figure 5: Automation outline executed using Python script.

5. APPROXIMATION ASSISTED OPTIMIZATION

The optimization problem is given by

$$\begin{aligned} &\max \ h \\ &\min \ \Delta P / L \\ &s.t. \begin{cases} 0.58 \le \dfrac{s_T}{2 s_L} \le 1.73 \\ 3.0 \le h \le 12.0 \\ 3.0 \le d_{sp} \le 10.0 \\ 0.1 \le v_{in} \le 2.0 \end{cases} \end{aligned} \tag{4}$$

The metamodel is developed using 408 simulations and verified using 103 random samples yielding a MAS value of 94.17% for heat transfer coefficient and 90.29% for pressure drop. The metamodel verification metrics (Simpson et al., 2001) are shown in Table 3.

Table 3: Metamodel verification metrics.

Interpolated variable	Heat Transfer Coefficient	$\Delta P / L$
Number of samples	408	
Number of random samples	103	
Correlation	Spherical	Spherical
Regression model	Polynomial 2nd order	Polynomial 2nd order
Relative RMSE (%)	1.83	2.15
MAS threshold (%)	10	10
MAS (%)	94.17	90.29

6. RESULTS

6.1 Sensitivity Analysis

After the metamodel is verified, it is used to conduct a sensitivity analysis on each of the four design parameters in order to test the effect of each parameter individually on the thermal-hydraulic performance of PPHXs. For each parametric study, a single variable is changed while all other variables are fixed. The reference values used for each design variable in all studies are 0.58 pitch ratio, 3.0 mm pillow height, 10.0 mm spot weld diameter, and 0.95 $m \cdot s^{-1}$ inlet velocity. Figure 6 shows the results of the pitch ratio study.

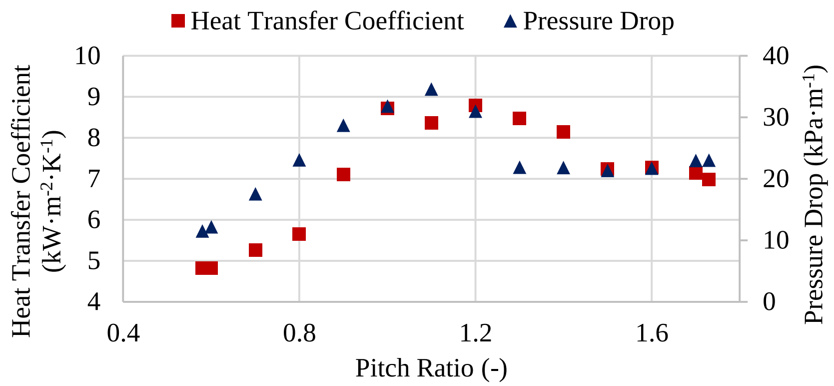

Figure 6: Sensitivity analysis for pitch ratio.

The spot weld pattern is transverse up to a pitch ratio of 1, and longitudinal for pitch ratios greater than 1. Longitudinal pitch ratio shows higher heat transfer coefficient as well as higher pressure drop values. This can be explained by the recirculation that takes place behind the weld occupying most of the narrow path between the welds. This leads to enhanced mixing but higher pressure drop as well. Figure 7 shows the results of the sensitivity study for the pillow height. It is found that a larger pillow height has a desirable effect on both higher heat transfer coefficient as well as a lower pressure drop per unit length. This is because a larger pillow height means a larger hydraulic diameter and thus the average channel velocity will be lower leading to lower pressure drop. It also implies a slightly larger heat trabsfer area which leads to a slight overall enhancement in the heat transfer coefficient as well. Figure 8 shows the results of the spot weld diameter sensitivity study. The results show that a smaller weld diameter is desirable for both enhanced heat transfer and reduced pressure drop. It is especially noted that the size of the weld greatly affect the hydraulic performance.

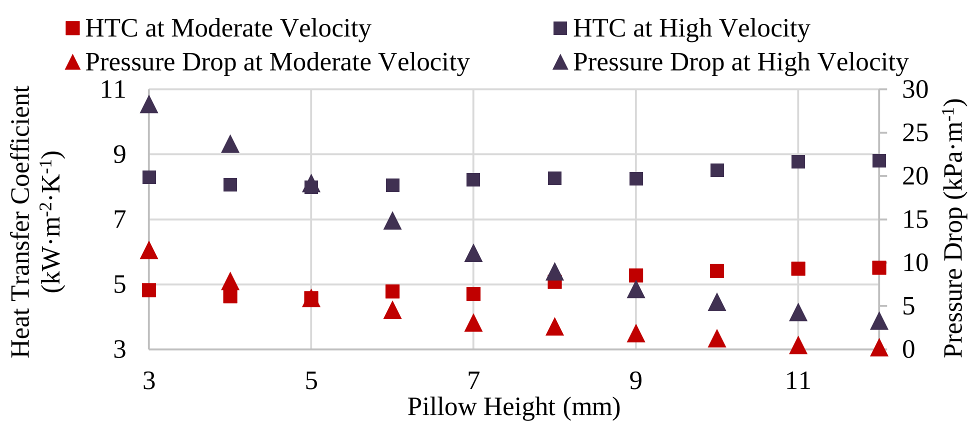

Figure 7: Sensitivity analysis for pillow height.

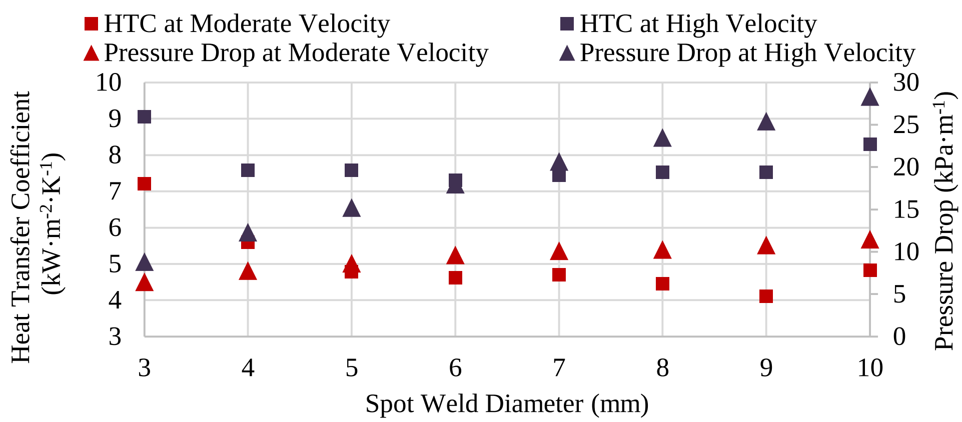

Figure 8: Sensitivity analysis for spot weld diameter.

Figure 9 shows the velocity profiles of two PPHX designs with different spot weld diameters. It can been seen from the velocity profiles that the PPHX design with larger weld diameter has a more restricted core flow zone yielding higher velocities due to the huge wake region behind the weld which not only deprives the design from heat transfer area required for higher heat transfer, but also lead to a higher pressure drop. This becomes well established and more obvious especially when steady state flow is attained. Finally, Figure 10 shows the results of the velocity sensitivity analysis. The inlet velocity greatly affects the thermal-hydraulic performance of PPHXs. The higher the inlet velocity the higher the heat transfer coefficient and also the higher the pressure drop which also increases at an even higher rate at very high inlet velocity values.

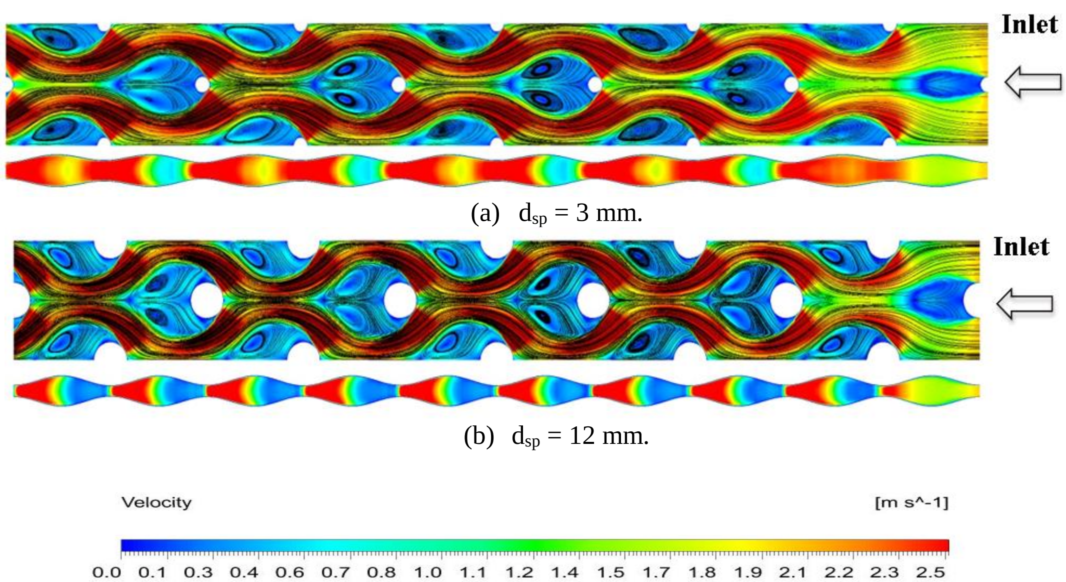

Figure 9: Velocity profiles for different spot weld diameters.

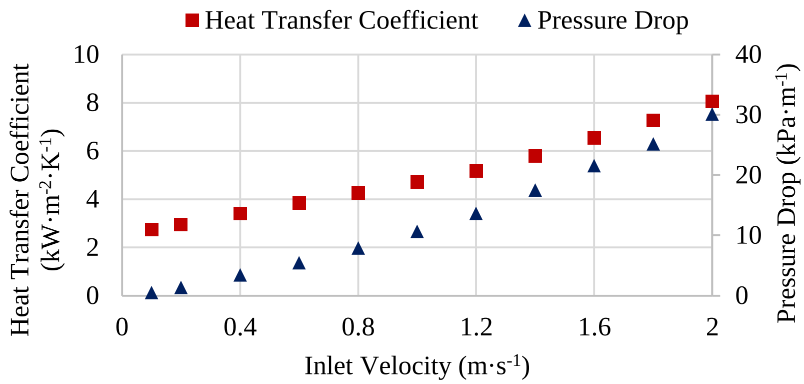

Figure 10: Sensitivity analysis for inlet velocity.

6.2 Optimal Designs

The verified metamodel is used to run a MOGA to optimize the thermal-hydraulic performance of PPHX. Figure 11 shows the optimum designs for the PPHX in comparison to the baseline. The baseline used for comparison in this study is one of the designs investigated by Piper et al. (2016) given in Table 2 and calculated at an inlet velocity of 1.2 $m \cdot s^{-1}$.

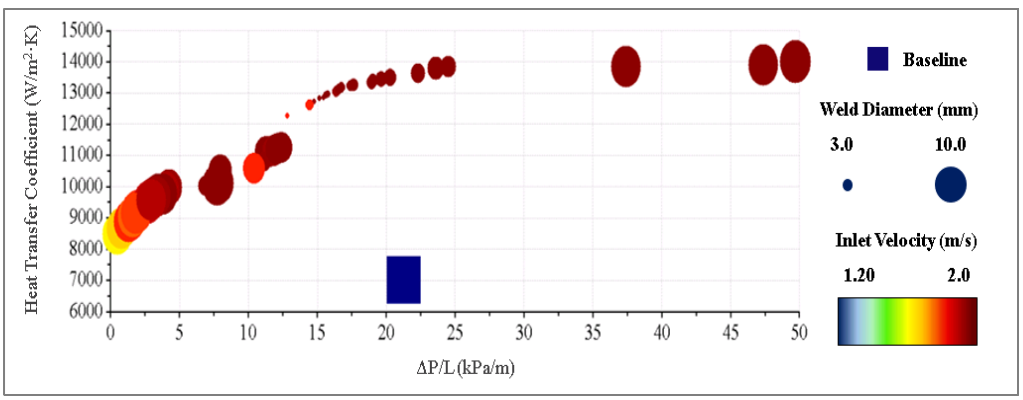

Figure 11: Optimum PPHX designs at different inlet velocity values and different weld diameters.

The spot weld diameter for the optimum designs ranged from 3 mm to 9.6 mm. The small diameters yield a higher heat transfer coefficient as well as a higher pressure drop, while the larger diameters yield a lower heat transfer coefficient and a lower pressure drop. However, at lower inlet velocities both heat transfer coefficient and pressure drop are low with larger spot diameter. Some of the best designs right at the middle of the Pareto have the smallest spot diameters balancing between higher heat transfer coefficient and moderate pressure drop values. The optimum PPHX designs have pitch ratios ranging from 0.58 to 1.4, pillow height ranging from 11.5 mm to 12 mm, and inlet velocity ranging from 1.7 $m \cdot s^{-1}$ to 2 $m \cdot s^{-1}$. This is quite expected as per the sensitivity analysis in spite of the fact that pressure drop increases as well at higher values of inlet velocities. The optimization results show a significant improvement in heat transfer coefficient of up to the double with respect to the baseline. The results also show a significant reduction in pressure drop per unit length of up to 98% reduction relative to the baseline.

7. CONCLUSIONS

A PPHX optimization study using PPCFD and AAO is presented. The method involves automating the simulation of novel PPHX geometries and using the responses to generate a metamodel which is verified by random designs to ensure acceptability. The metamodel is then used to conduct a sensitivity analysis which reveals that a smaller weld diameter has a significantly favorable effect on both heat transfer and pressure drop. The sensitivity analysis clearly shows that the weld size is the most promising parameter that can be varied to further improve the thermal-hydraulic performance of PPHXs. Multiobjective optimization is run on the metamodel as well to optimize the performance of PPHXs. The optimal designs show a significant improvement in heat transfer coefficient which can be up to double the baseline and a significant reduction in pressure drop per unit length of up to 99% reduction relative to the baseline.

NOMENCLATURE

A_w	wetted area	(m^2)	h_p	pillow height	(m)
d_h	hydraulic diameter	(m)	v_{in}	inlet velocity	($m \cdot s^{-1}$)
d_{sp}	spot weld diameter	(m)	s_L	Longitudinal spot weld pitch	(m)
GCI	Grid Convergence Index	(-)	s_T	transverse spot weld pitch	(m)

REFERENCES

Abdelaziz, O. (2009). *Development of multi-scale, multi-physics, analysis capability and its application to novel heat exchanger design and optimization.* College Park, MD: PhD Thesis presented to the Department of Mechanical Engineering at the University of Maryland.

Abdelaziz, O., Aute, V., Azarm, S., & Radermacher, R. (2010). Approximation-Assisted Optimization for novel compact heat exchangers. *HVAC&R Research, 16*(5), 707-728.

ANSYS Inc. (2016). ANSYS 17.0. www.ansys.com.

Cressie, N. (1993). *Statistics for Spatial Data.* New York: John Wiley & Sons.

Deb, K. (2001). *Genetic algorithms for optimization.* Kanpur, India: KanGAL Report No. 2001002.

Deb, K. (2011). *Multi-Objective Optimization Using Evolutionary Algorithms: An Introduction.* KanGAL Report Number 2011003.

Eldeeb, R., Aute, V., & Radermacher, R. (2016). Investigation of Thermal-Hydraulic Characteristics of Pillow Plate Heat Exchangers Using CFD. *16th International Refrigeration and Air Conditioning Conference at Purdue, Paper 2278.*

Hamad, H. (2006). A new metric for measuring metamodels quality-to-fit for deterministic simulations. *Proceedings of the 2006 Winter Simulation Conference.*

Hilbert, R., Janiga, G., Baron, R., & Thevenin, D. (2006). Multi-objective shape optimization of a heat exchanger using parallel genetic algorithms. *International Journal of Heat and Mass Transfer, 49*, 2567–2577.

McKay, M., Beckman, R., & Conover, W. (1979). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics, 21*, 239-245.

Mitrovic, J., & Maletic, B. (2011). Numerical Simulation of Fluid Flow and Heat Transfer in Thermoplates. *Chemical Engineering & Technology, 34*(9), 1439-1448.

Mitrovic, J., & Peterson, R. (2007). Vapor Condensation Heat Transfer in a Thermoplate Heat Exchanger. *Chemical Engineering & Technology, 30*(7), 907-919.

Piper, M., Olenberg, A., Tran, J. M., & Kenig, E. Y. (2015). Determination of the Geometric Design Parameters of Pillow-Plate Heat Exchangers. *Applied Thermal Engineering, 91*, 1168-1175.

Piper, M., Olenberg, A., Tran, J. M., & Kenig, E. Y. (2016). Numerical Investigation of Turbulent Forced Convection Heat Transfer in Pillow Plates. *International Journal of Heat and Mass Transfer, 94*, 516-527.

Piper, M., Zibart, A., & Kenig, E. Y. (2017). New Design Equations for Turbulent Forced Convection Heat Transfer and Pressure Loss in Pillow-Plate Channels. *International Journal of Thermal Sciences, 120*, 459-468.

Roache, P. J. (1998). *Verification and Validation in Computational Science and Engineering.* Hermosa Publishers.

Simpson, T. W., Peplinski, J. D., Koch, P. N., & Allen, J. K. (2001). Metamodels for Computer-based Engineering Design: Survey and Recommendations. *Engineering with Computers, 17*(2), 129-150.

Tran, J. M., Linnemann, M., Piper, M., & Kenig, E. Y. (2017). On the Coupled Condensation-Evaporation in Pillow-Plate Condensers: Investigation of Cooling Medium Evaporation. *Applied Thermal Engineering, 124*, 1471-1480.

ACKNOWLEDGEMENT

This work was supported by the Modeling and Optimization Consortium (MOC) of the Center for Environmental Energy Engineering (CEEE) at the University of Maryland College Park.