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An Improved Approach for Modeling Plate Heat Exchangers Based on Successive Substitution in Alternating Flow Directions

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ABSTRACT

Finite volume modeling of plate heat exchangers is challenging in terms of computation time and robustness, especially in two-phase flow due to the coupling of pressure drop and heat transfer equations. Usually the entire heat exchanger is divided into segments and solved iteratively. Many thermophysical property calculations are required for each channel in each segment which is computationally expensive, especially with a high number of iterations. This led some models to employ pre-defined databases with many correction factors to overcome slow and unstable computation. In order to overcome this, an improved approach is developed for the analysis of plate heat exchangers with multi-fluid, multi-stream, and multi-pass configurations. The model is capable of handling simultaneous phase change in all channels. In the proposed approach, the fluid properties are propagated in one flow direction, while the fluid properties in the opposite direction are calculated in a given iteration. These operations are switched in the next iteration. The convergence of this approach is verified numerically. This approach shows significant improvement in computation speed and robustness compared to current models. This approach solves 6-12 times faster in terms of number of iterations required to solve a plate heat exchanger and more stable especially with a lower number of segments compared to existing model. The model is validated against 150 in-house experimental data points for single phase water, two-phase ammonia, R22 boiling, two-phase R134a, and R410A condensation. Overall, the model predicts heat capacity within 5%.

1. INTRODUCTION

Plate heat exchangers (PHXs) are becoming increasingly popular in the heating, ventilating, air-conditioning, and refrigeration (HVACR) industry due to their high effectiveness and compactness. Whether it is a chevron-plate, pillow-plate (Piper et al., 2015), or even plain-flat-plate, or other types of PHXs, they are characterized by high heat load per unit volume with the brazed/welded type being able to withstand high pressure levels. Computer models are essential for design and development of state of the art heat exchangers. It is widely accepted that they significantly reduce design and development time, as well as capital and operational costs. With the encouraging characteristics of PHXs, it is highly desirable to use computer models to develop and optimize PHX designs in order to maximize energy efficiency.

However, there are limited computer models available for PHXs. The PHX problem is complex in nature. The number of unknowns in a PHX problem is equal to two times the number of channels minus one or $2(N-1)$, where N is the number of channels. With phase change and more complex flow configurations, the problem becomes even more challenging. The PHX is divided into a number of segments M resulting in a matrix of $2(N-1)\times M$ unknowns which requires extensive thermophysical property calculations and great computational effort to be solved. Numerically, the problem can also be unstable depending on the quality of the discretization method and due to the interdependence between the heat transfer and pressure drop calculations.

Kandlikar and Shah (1989), Zaleski and Klepacka (1992), Georgiadis and Macchietto (2000), Ribeiro & Caño Andrade (2002), and Gut and Pinto (2003), developed various models for plate heat exchangers. Some literature proposed procedures to solve parallel flow, series flow, or flow with predefined configurations. Some propose algorithms to solve general configurations with no phase change with constant heat transfer coefficient all over the PHX due to lack of information on correlations at the time. Flow maldistribution was not accounted for in most of the studies. The algorithm developed by Ribeiro & Caño Andrade (2002) was used in an industrial milk pasteurization simulation tool which is only used for single-phase heat transfer flow. In single-phase flow, the heat transfer and pressure drop equations can be decoupled, unlike the two-phase flow which is the common case in HVACR applications.

The finite volume semi-explicit method for wall temperature linked equations (SEWTLE) approach developed by Corberán et al. (2000) was employed by Gullapalli (2013) in a generalized rating method used in a specific industrial tool for the selection of brazed PHXs. However, the developed model is not fully implemented in the commercial PHX selection software due to speed limitations and to improve stability. Instead, the detailed geometry of the plate is read from a product database. In-house empirical constants for single-phase and two-phase heat transfer coefficient and pressure drop correlations are also read from a product database. Also, all boundary temperatures must be specified by the user. This makes the tool good for the commercial purpose it was developed for, but negates its flexibility to design or simulate any PHX that is outside this product database. There are other very few commercial PHX simulation tools, but there is no enough information available to reveal information about these tools, such as flexibility, whether empirical factors for certain databases are used, speed, or the robustness of the tool.

Qiao et al. (2013) developed a mathematical model that is employed in a PHX simulation tool which distinguishes itself by providing the greatest flexibility and pass configuration generality using the concept of "Junction-Channel Connectivity Matrix". The tool developed also allows customization features such as using a user-defined heat transfer coefficient or pressure drop correlation, in addition to built-in correlations from literature. The tool has the most up to date and comprehensive libraries of working fluids and allows for user-defined mixtures as well. However, with the generality comes the challenges of stability and speed limitations. The stability is greatly improved using efficient routines for initial guess wall temperatures calculation and numerical convergence.

This study introduces an improved algorithm for the model developed by Qiao et al. (2013) to improve the model's speed while maintaining the flexibility features required to develop any PHX design, while maintaining the thermal-hydraulic accuracy and stability of the model. Using the improved approach, the speed is improved by at least 2-16 times in terms of both the number of iterations required to achieve convergence and the simulation time required. This developed model will make the simulation of PHXs easier and favorable, and thus allowing significant improvement of PHX design. More energy efficient PHX designs can potentially be the next generation of compact, highly energy efficient, heat exchangers which can have a lot of favorable implications such as significantly reducing the environmental impact.

2. IMPROVED APPROACH OUTLINE

The model introduced by Qiao et al. (2013) adopts a successive substitution approach where the PHX is divided into a number of segments, M , of equal size and each segment can be solved individually. To solve each segment in a counter flow PHX, properties are calculated for each channel in each slice at the outlet and at the inlet in each iteration. Although the model is very stable, this is very computationally expensive. Solving the segments in parallel saves on computational time, however, this approach has a slow convergence and extensive thermophysical property calculations. Qiao et al. (2013) employs an implicit quasi-Newton numerical method to solve for the unknowns in each segment. Another option is to employ explicit equations such as those in SEWTLE method (Corberán et al., 2000). However, implicit methods are more robust compared to explicit methods although computationally expensive. So it is required to maintain the stability of the solution, while optimizing the number of thermophysical property calculations required and result in good accuracy.

The improved approach divides the flow in the PHX into two types according to the flow direction, namely, upward flow and downward flow irrespective of the kind of fluid in the channel or the phase of the fluid. As shown in Figure 1, one of the directions is the primary flow in a given iteration, and this is the solution direction in the current iteration.

The properties are propagated in this direction for the primary flow, while the other flow is solved using the successive substitution approach. An example is given in Figure 1 (a). This will accelerate the solution in the direction of the primary flow. In the next iteration, as shown in Figure 1 (b), the directions are alternated such that the other direction becomes the primary flow. Then the properties propagate in this direction, while the other direction is solved using the successive substitution approach. This is alternated in the next iteration and so on.

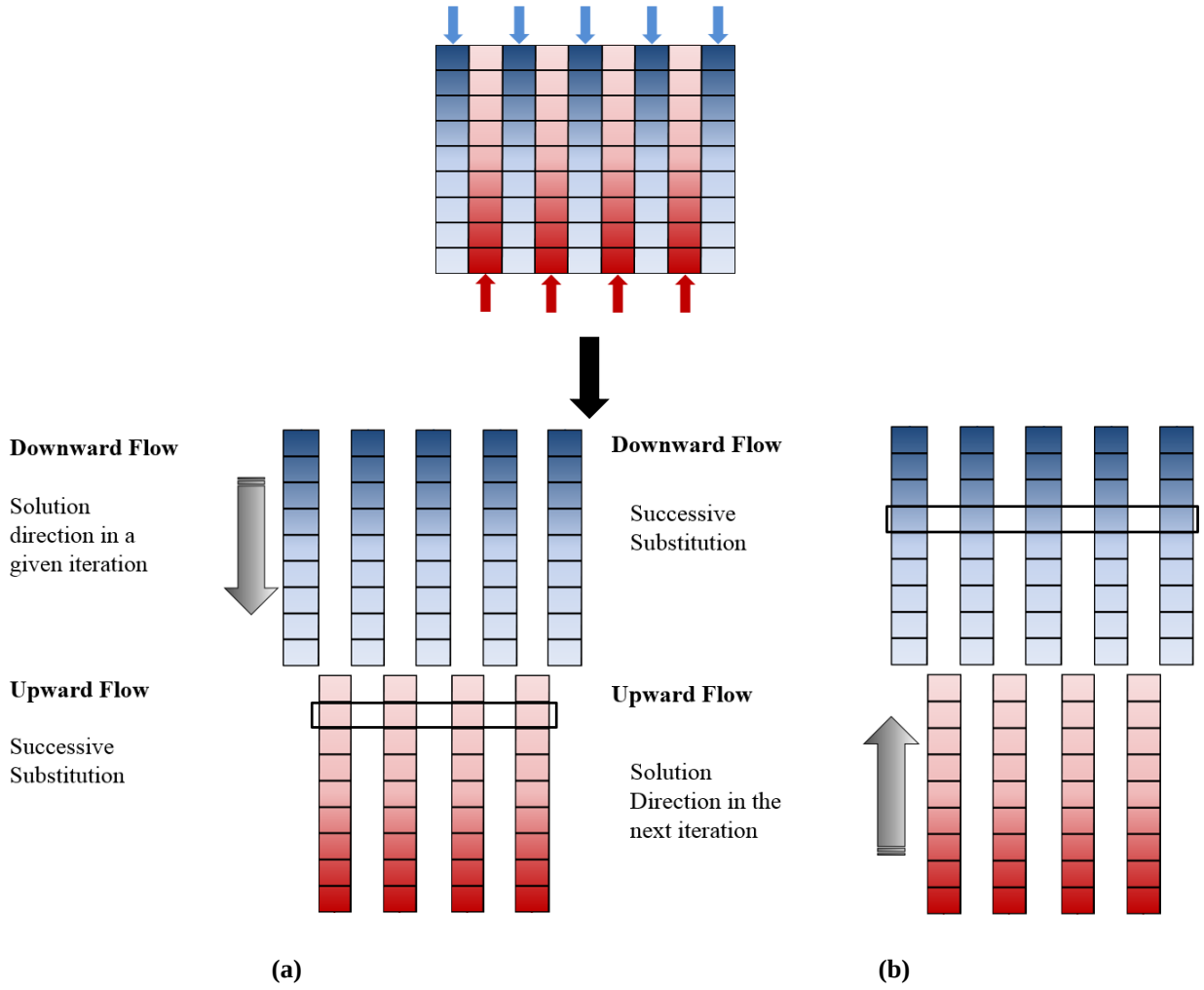


Figure 1: Improved solver outline (a) iteration in downward directions, (b) iteration in upward direction.

One drawback in this approach is that the parallel calculation of the slices cannot take place anymore. However, the speed benefit from solving the PHX using this approach is much more significant than the benefit of the parallel solution of segments.

To test the convergence of this improved approach, there are two aspects to look at. First, in terms of heat transfer, it is possible for temperature crossing to take place between the fluids or the numerical solution to diverge due to the acceleration of the solution in a certain direction. However, this is avoided as the initial guess wall temperatures are calculated the same way for both approaches using the following explicit equation

$$T_{w,i} = \frac{U_{r,i-1}T_{in,i-1} + U_{l,i}T_{in,i}}{U_{r,i-1} + U_{l,i}},\ i = 1\ to\ N \tag{1}$$

Using this equation, the guess wall temperatures are well predicted to achieve numerical convergence. The heat transfer coefficients are pre-evaluated using the inlet conditions. This calculation takes place at the beginning of the first iteration. The numerical solution used in this model requires a very good initial guess value for the dependent variable which is the wall temperatures in the PHX problem. This is ultimately achieved using Equation (1). Also, the temperature difference between the preceding and adjacent control volumes actually becomes smaller due to the accelerated solution, which makes the solution more stable.

Second, numerically the solution must achieve convergence. The solution is said to reach final convergence when the state of the solution is correct and does not change. The "four basic rules", stated by Patankar (1980), that promote convergence are as follows

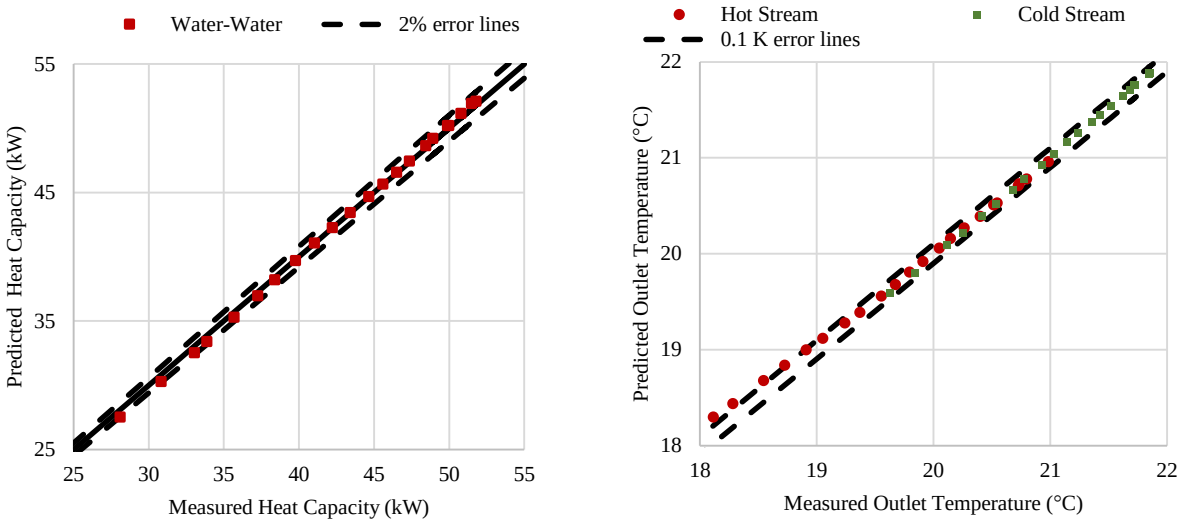
1. Consistency at control volume faces: the wall of the PHX represents a common face for two adjacent channels. In each segment, the wall is the common face for two adjacent control volumes. The heat flux across the wall is represented by the same expression in the discretization equation for both control volumes (Qiao et al., 2013). This is the case in both approaches.
2. Positive coefficients in the iterative procedure: assumptions 2 to 4 in Qiao et al. (2013) state that the plate surface temperature, the phase of the fluid, and the heat transfer coefficient are assumed to be constant within a segment. The same assumptions are maintained with the current approach. The assumptions guarantee that the coefficients of the iterative procedure within each segment will have the same sign, i.e. positive.
3. Negative slope linearization of the source term. In the PHX problem, there is a negative-slope relationship between the heat flux, which is the source term, and the dependent variable which is the wall temperature as the wall temperature decreases as heat is added to the control volume and vice versa. Therefore, this rule is applied as well.
4. Summation of neighboring coefficients. This rule implies that the center point temperature must be a weighted average of the neighbor temperature values which is applied, again due to the assumptions stated in 2.

Therefore, the current approach does not violate any of these rules. However, Patankar (1980) also mentions that it is very difficult to always guarantee convergence with all the interlinkages present is such complicated problems. But by having the basic rules in place, and solving the correct problem, thermal and numerical convergence can be achieved, i.e. the solution will converge to the correct answer.

3. VALIDATION

Experimental data sets that were previously used by Qiao et al. (2013) and Eldeeb et al. (2014) are used to validate the improved approach, in addition to few other data points. Throughout this study, the single-phase correlation developed by Yan and Lin (1999) is used for single-phase heat transfer coefficient calculation, and the correlation developed by Muley and Manglik (1999) is used for single-phase pressure drop calculation.

A single phase water-water data set is used with 22 data points. Using the improved approach, the heat capacity and the outlet temperatures of both streams are calculated and shown in Figure 2. The heat capacity for all cases is within 2% showing a very strong agreement with the experimental results. Most of the outlet temperatures for both streams are within 0.1 K, with very few points within 0.2 K.



(a) **(b)**

Figure 2: Comparison between predicted and experimental (a) heat capacity, and (b) outlet temperature of improved solver for water-water single phase.

Water-R134a condensation data set with 12 data points is used to validate the prediction of heat capacity using the new approach. The results from the improved approach versus the experimental results are shown in Figure 3. The heat capacity is within 5% for most data points with two data points within 7%. In this study, the condensation heat transfer coefficient correlation developed by Yan et al. (1999) for plate heat exchangers, and the widely accepted (Wang et al., 2000) pressure drop correlation developed by Lockhart and Martinelli (2000) are used.

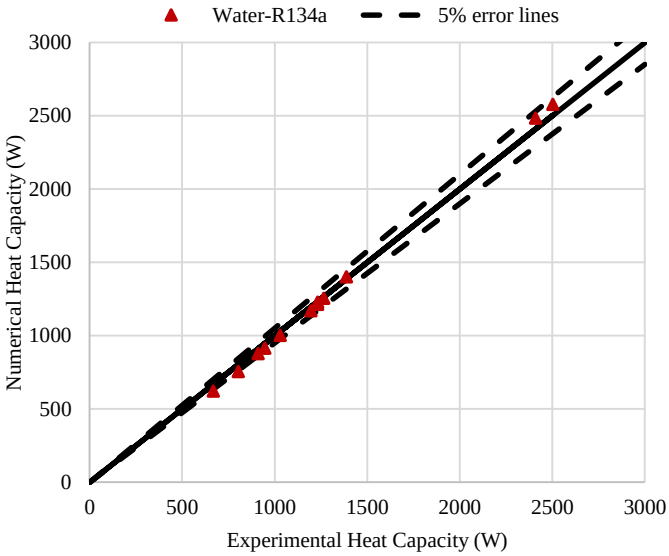
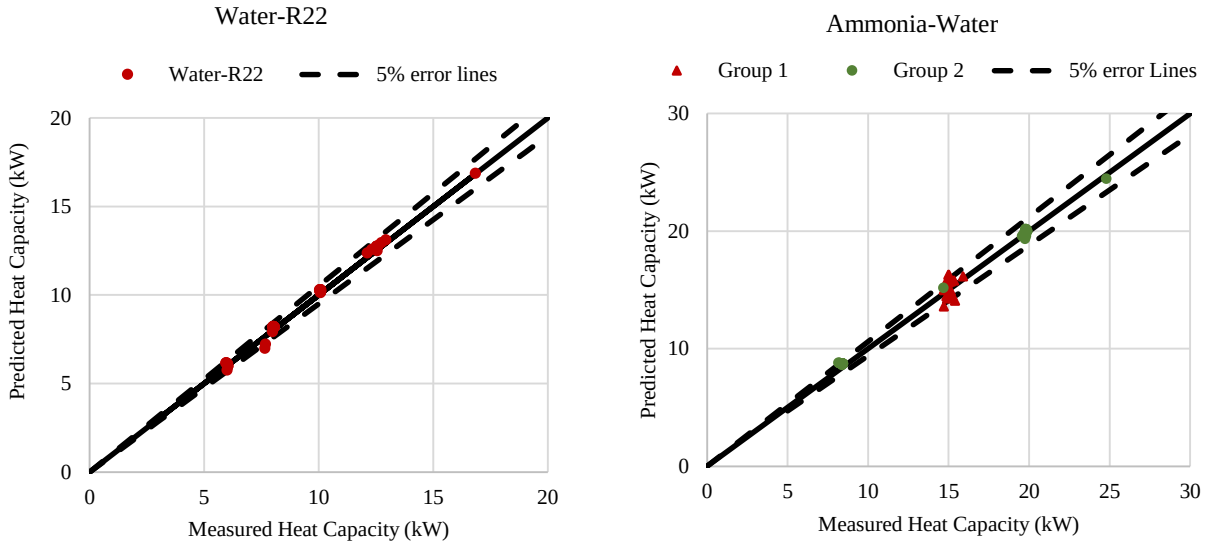


Figure 3: Comparison between predicted and experimental heat capacity of improved solver for water-R134a condensation.

Figure 4 shows the validation of the improved approach using experimental results of three datasets. The evaporation heat transfer coefficient and pressure drop correlations developed by Khan and Chyu (2010) for plate heat exchangers

are used in this study. Figure 4 (a) shows water-R22 predicted heat capacity using the improved approach against the experimental results. This data set has 58 data points with 49 points within 3% of the experimental results. The improved approach solved 15 cases which failed to solve using the approach presented in Qiao et al. (2013).



(a) **(b)**

Figure 4: Comparison between predicted and experimental heat capacity for (a) water-R22, and (b) ammonia-water, of improved solver for evaporation.

Figure 4 (b) shows two data sets of ammonia-water evaporation. Group 1 contains 25 data points, with 19 points within 6% of the experimental results and the remaining points lie within 9%. In this data set, 8 cases that failed to solve by the current solver and were not presented in Qiao et al. (2013) are solved by the improved approach. Group 2 contains 32 data points with 28 of these points within 5% of the experimental results and the remaining points are within 8%. Qiao et al. (2013) only presented 12 of these points. Generally, the improved approach is more robust than the model developed by Qiao et al. (2013). Finally, few data points using propylene glycol 30% and carbon dioxide PHX are also validated, with the heat load within about 3%.

4. VERIFICATION

The improved approach is verified against the approach developed by Qiao et al. (2013) using a test matrix containing 7246 PHX cases. The cases include condensers, evaporators, and single-phase PHXs. The refrigerants used in the matrix include water, R410A, R134a, ammonia, R22, propylene glycol 30%, and carbon dioxide. The success rate of the improved approach is higher than 98%, which makes the solution very stable compared to about 40% success rate of Qiao et al. (2013).

In the most trivial case of parallel flow in all channels, the PHX will simply solve in one iteration using the improved approach rather than M iterations using successive substitution, no matter how many segments are used in the PHX. This is four times faster in terms of time of simulation. In a more complicated case where the flow is counter and phase change takes place in all channels at the same time, the number of iterations is 22 times faster and the solution speed is 5 times faster. For the test matrix developed, the improved approach proved to be more robust with 7% of the cases solving only with the new approach, especially for a lower number of segments. The new approach is at least 2-16 times faster than the approach developed by Qiao et al. (2013). For the 7246 cases, the solution is on average 7 times faster than the approach developed by Qiao et al. (2013).

5. CONCLUSIONS

This paper introduces a very simple, yet significantly faster and more stable approach to model PHX. The approach builds on an existing model, but provide much faster solution time and higher stability without compromising the accuracy of the solution. The developed PHX solver does not require any empirical coefficients or the use of certain product databases to ensure stability and speed, in contrary it is very flexible in terms of design and pass configuration. The heat transfer coefficient and pressure drop are calculated using correlations available in literature based on the fluid properties in each segment in each iteration or even user-defined correlations or values. The improved approach is validated using experimental data from five different datasets, that include single phase flow, boiling and condensation including few glycol-carbon dioxide condensation cases. The improved approach is also extensively verified against the model of Qiao et al. (2013) using a test matrix with 7246 cases showing great agreement with heat capacity and pressure drop values, with the improved approach solving in a much smaller number of iterations and at least 2-16 times faster. The improved approach also shows greater stability especially with a lower number of segments as proven by running the verification matrix achieving a success rate higher than 98%.

NOMENCLATURE

M	number of segments	(–)
N	number of channels	(–)
T	temperature	(K)
U	heat transfer coefficient	(W/m·K)

Subscript

in	inlet
l	left
r	right
w	wall

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