Plate Heat Exchanger: Effects of Temperature Difference and Liquid Flow Rates on Heat Transfer Coefficients

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Abstract

Plate heat exchangers are among the most common heat transfer methods in numerous industries, like HVAC, refrigeration, chemical processing, and more. In this experiment, we examined the impact of adjusting volumetric flow rate of both hot and cold streams entering a counter-flow plate heat exchanger by determining non-linear regression coefficients for an empirical Nusselt correlation for the system and analyzing the difference between measured and predicted heat transfer coefficients. Our results indicated that compact turbulent flow within the heat exchanger was present, which was consistent with literature that have analyzed the Nusselt correlation used. Additionally, we noted trends from the measured heat transfer coefficients that match well with predicted values, suggesting high heat transfer efficiency and energy conservation within the system. The experiment is very narrow in scope, however, so future work should be done to analyze plate heat exchangers' relationship with different volumetric flow rate differences or to compare the effects of different liquids or plate materials with varying thermal conductivities and liquid flow directions (counter-flow versus cross-flow).

1 Introduction

Heat transfer is a core concept in chemical engineering, and frankly, almost any field and day-to-day activity in the modern world. Industrialized methods for heat transfer are necessary in almost any process, and as a result, many different types of heat exchangers have been designed to fit processes in various industries like air conditioning, pharmaceutical, chemical, refrigeration, and power plants.[1]

The most common type of heat exchanger is a shell-and-tube heat exchanger, in which one fluid enters and exits on the edges flows through a bundle of tubes down the middle of the heat exchanger, while the other fluid flows within the shell, transferring heat through the walls of tubes, aided by baffles within the shell to direct flow and improve efficiency.[1,2]

The other common heat exchanger is the plate heat exchanger, where a series of metal plates are lined together such that alternating channels of warm and cold liquid flow between them. Hot and cold pipes run through holes within the array of plates allowing liquid to fill the channels, and heat transfer in the form of conduction and convection occurs through the plates, dependent on the metal's thermal conductivity. Plate heat exchangers are generally much cheaper due to their smaller size, are much more efficient, and are less susceptible to fouling than shell-and-tube heat exchangers, but they also cannot withstand high temperature and pressure environments like shell-and-tube heat exchangers can.[3]

Plate heat exchangers can be further split into three types: gasket, brazed, and welded, each with unique advantages. Gasket plate heat exchangers are notable for being able to easily add and remove plates, keeping maintenance costs low and allowing for design flexibility.[3] Brazed plate heat exchangers seal plates together completely with filler metals like copper or nickel, lowering installation costs and preventing leaks, while welded plate heat exchangers are especially useful for high temperatures or corrosive materials, but can't be properly cleaned as plates are welded together.[4]

2 Background

Plate heat exchangers (PHEs) offer high thermal performance and compactness, making them vital in many industries.[5] The overall heat transfer coefficient (U) is a key metric for PHE efficiency, reflecting combined convective and conductive thermal resistances. Accurate U determination is crucial for PHE design and operational optimization.

Experimental studies are fundamental to understanding PHEs. Eldean et al. [6] focused on correlations for single-phase convection in brazed PHEs, while Farraj and Hrnjak [7] validated correlations for heat transfer and pressure drop. The significant impact of working fluid properties on performance was demonstrated by Song et al. [8]. These studies typically aim to refine Nusselt number correlations for predicting convective coefficients.

PHE performance analysis relies on empirical correlations from experimental data. Yang et al. [5] provided a detailed methodology for developing such correlations, which informs this study. A practical experimental challenge is maintaining constant inlet temperatures, especially if fluid recycling occurs, potentially affecting data reliability.

Here, we experimentally determine the overall heat transfer coefficient (U) for a specific PHE. Adapting the methodology of Yang et al. [5], this work derives Nusselt number correlation constants, C_1 and C_2, by fitting to measured U values. The objective is to characterize the PHE's thermal performance, considering fluid properties and material resistances, to assess its operational efficiency.

3 Theory

The thermal analysis of the plate heat exchanger involves fundamental dimensionless numbers, heat transfer correlations, and the overall heat transfer coefficient. The specific geometric parameters of the PHE, such as projected heat transfer area (A_{proj}), hydraulic diameter (D_h), plate thickness (t_p), plate thermal conductivity (k_p), corrugation depth (b), effective channel width (W_1), and the number of channels for hot (n_h) and cold (n_c) fluids, are crucial for these calculations. While their specific values define the particular system under study, the theoretical framework presented here applies generally.

The fluid flow and heat transfer characteristics are described using the following dimensionless numbers:

The Reynolds number (Re) indicates the flow regime:

$$Re = \frac{\rho V D_h}{\mu} \tag{1}$$

where ρ is the fluid density, V is the mean fluid velocity within a channel, D_h is the hydraulic diameter, and μ is the dynamic viscosity. The hydraulic diameter for PHE channels is defined as:

$$D_h = 2b \tag{2}$$

where b is the corrugation depth. The mean fluid velocity (V) in a channel is:

$$V = \frac{\dot{m}}{\rho n W_1 b} \tag{3}$$

where $\dot{m}$ is the mass flow rate, n is the number of channels for the specific fluid (hot or cold), and W_1 is the effective width of one channel.

The Prandtl number (Pr) relates momentum diffusivity to thermal diffusivity:

$$Pr = \frac{c_p \mu}{k} \tag{4}$$

where c_p is the specific heat capacity and k is the thermal conductivity of the fluid. For this experiment, water is used as the working fluid for both streams. Its properties (ρ, μ, c_p, k) are temperature-dependent and are evaluated using cubic polynomial fits derived from NIST data over the $20 - 80\,°\mathrm{C}$ range.

The Nusselt number (Nu) represents the ratio of convective to conductive heat transfer:

$$Nu = \frac{hD_h}{k} \tag{5}$$

where h is the convective heat transfer coefficient.

The Nusselt number for single-phase flow in PHEs is empirically correlated to the Reynolds and Prandtl numbers. Based on the approach similar to Yang et al. (2017) and the experimental plan, the viscosity correction factor $(\mu/\mu_w)^{C_4}$ is assumed to be unity. Thus, the correlation takes the form:

$$Nu = C_1 Re^{C_2} Pr^{1/3} \tag{6}$$

The constants C_1 and C_2 are specific to the heat exchanger geometry and flow conditions and are determined experimentally. The exponent for the Prandtl number (C_3) is taken as $1/3$.

The experimentally measured overall heat transfer coefficient ($U_{measured}$) is determined from:

$$U_{measured} = \frac{Q_{measured}}{A_{proj}\Delta T_{LMTD}} \tag{7}$$

where A_{proj} is the projected heat transfer area. The measured heat transfer rate, $Q_h = \dot{m}_h c_{p,h}(T_{h,in} - T_{h,out})$ and $Q_c = \dot{m}_c c_{p,c}(T_{c,out} - T_{c,in})$. The log mean temperature difference (ΔT_{LMTD}) for counter-current flow is:

$$\Delta T_{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \tag{8}$$

The constants C_1 and C_2 in Equation 6 are determined by fitting a model to the experimentally obtained $U_{measured}$ values. This involves a non-linear regression procedure.

The model for $U_{calculated}$ is based on the overall thermal resistance, neglecting fouling:

$$\frac{1}{U_{calculated}} = \frac{1}{h_{h,calc}} + \frac{t_p}{k_p} + \frac{1}{h_{c,calc}} \tag{9}$$

The individual calculated convective heat transfer coefficients, $h_{h,calc}$ and $h_{c,calc}$, are obtained using the Nusselt correlation (Equation 6) for given trial values of C_1 and C_2:

$$h_{h,calc} = \frac{k_h}{D_h}\left(C_1 Re_h^{C_2} Pr_h^{1/3}\right) \tag{10}$$

$$h_{c,calc} = \frac{k_c}{D_h}\left(C_1 Re_c^{C_2} Pr_c^{1/3}\right) \tag{11}$$

The non-linear regression algorithm adjusts C_1 and C_2 to minimize the sum of squared differences between $U_{measured}$ (from Equation 7) and $U_{calculated}$ (from Equation 9 using Equations 10 and 11) over all experimental data points. The resulting best-fit C_1 and C_2 values define the specific heat transfer correlation for the tested PHE. These values are then used to compute the final $U_{calculated}$ values for comparison against $U_{measured}$.

4 Methods

A plate heat exchanger was created by placing 7 316 stainless steel plates (0.6 mm thick) next to each other, allowing for 6 channels of liquid to flow through. The inner and outer length and width are measured, as are the area of the circles in which the pipes connect to the plates. Two large tanks, one empty, one full of DI water, are connected to the plate heat exchangers such that water enters from the full one and exits into the empty one-this is the "cold stream"-while piping is also connected to a water heater that supplies warm water to the system. The two entering streams are sent through different channels, allowing for heat transfer to occur through the plates dependent on their thermal conductivity.

For each trial, volumetric flow of hot and cold flows were both randomized between 1 and 10 GPM. Thermocouples are attached at both inlets and outlets of cold and hot streams and measured electronically to determine the temperature difference and develop a non-linear regression that represents the heat transfer between the streams.

5 Results

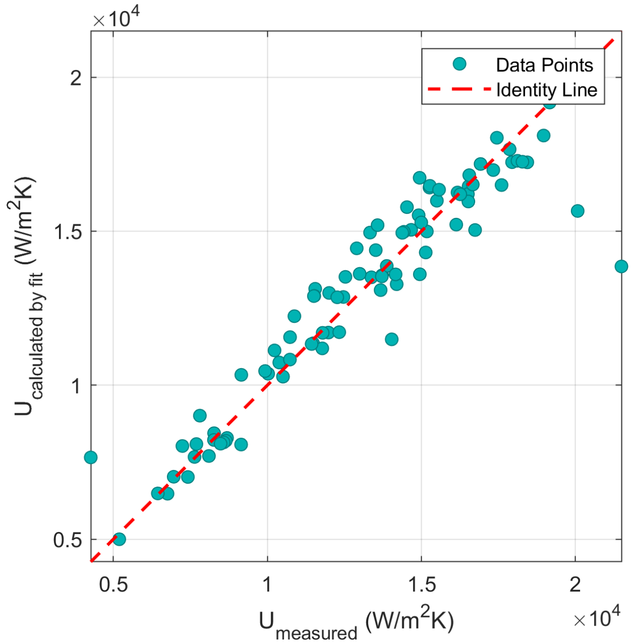

Figure 1: Comparison of predicted and measured heat transfer coefficients. Calculated overall heat transfer coefficients U_{calc} were obtained from the best-fit values of C_1 and C_2 using nonlinear regression, and plotted against experimental values U_{meas}. Each point represents a trial. The dashed identity line ($y = x$) is provided for reference. Strong alignment with the identity line supports the accuracy of the chosen empirical model for this flow configuration.

Parameter	**Fitted Value**	**95% Confidence Interval**
C_1	0.0856	[0.0339, 0.1374]
C_2	0.9370	[0.8624, 1.0115]

Table 1: Fitted correlation coefficients and 95% confidence intervals.

The empirical model for convective heat transfer in the plate heat exchanger was fitted to the measured data using nonlinear regression. The resulting correlation constants were $C_1 = 0.0856$ and $C_2 = 0.9370$, with corresponding 95% confidence intervals listed in Tab. 1. These values were applied to calculate predicted overall heat transfer coefficients, U_{calc}, which were compared to the experimentally measured coefficients, U_{meas}.

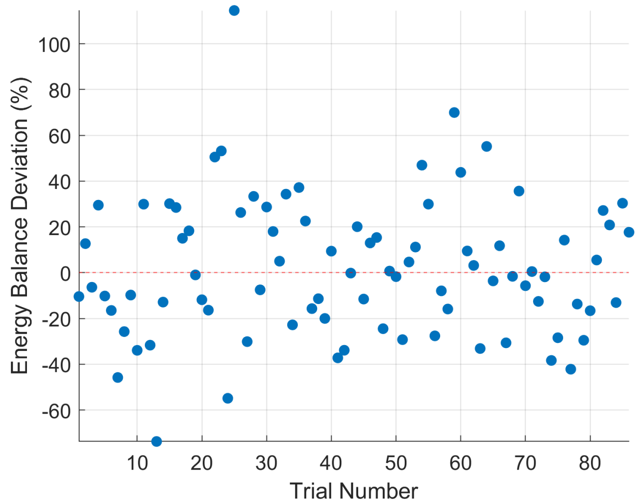

Figure 2: Energy Balance Deviation (EBD) across all trials. EBD was calculated for each trial as the percent difference between heat transfer rates on the hot and cold sides, normalized by their average. Positive values indicate the hot stream lost more energy than the cold stream gained; negative values suggest the opposite. A majority of data points cluster near this line, and 95% of all trials showed deviations within ±54.91%, suggesting that while some outliers exist, the system maintained reasonably consistent energy conservation across trials.

As shown in Fig. 1, the calculated coefficients generally followed the identity line $U_{\text{calc}} = U_{\text{meas}}$, indicating strong agreement between the model and the experimental results. Most data points cluster near the line, suggesting that the chosen empirical form captures the system's behavior over the tested range of conditions.

Energy Balance Deviations (EBD) across all trials are presented in Fig. 2. Each point represents the percent difference in energy transfer rate between the hot and cold streams for one trial, normalized by the average of the two. The dashed horizontal line at 0% represents perfect energy balance.95% of trials showed energy balance deviations within ±54.91%. Although deviations were both positive and negative, a majority of trials fell within ±30% of balance.

No data points were excluded from analysis. All results shown are from raw, unfiltered data using the full trial set. An approximate experimental efficiency was estimated from the EBD using the expression Efficiency $= 1 - \frac{\text{EBD}}{100}$. Based on this, most trials exhibited efficiencies above 70%, with a maximum of approximately 95%. These values reflect how effectively energy was conserved between the hot and cold streams under the given flow conditions.

6 Discussion

As described in Eq. (6), heat transfer performance in PHEs is often characterized using an empirical Nusselt number correlation of the form, which captures convective behavior across varying flow regimes. The constants C_1 and C_2 depend on the exchanger's geometry and flow conditions, and are typically determined via nonlinear regression from experimental data.[5]

In this experiment, regression of measured data yielded best-fit values of $C_1 = 0.0856$ and $C_2 = 0.9370$, with 95% confidence intervals of [0.0339, 0.1374] and [0.8624, 1.0115], respectively (Tab. 1). These values fall within the expected range reported for turbulent flow in compact PHEs, where C_1 generally varies from 0.03 to 0.2 and C_2 approaches unity for fully developed turbulence.[6,7]

Fig. 1 compares the predicted U_{calc} values to the experimentally determined U_{meas}. The data show strong alignment with the identity line $y = x$, suggesting that the empirical model effectively captures the dominant heat transfer behavior across the tested range of Reynolds and Prandtl numbers. Minor deviations from the identity line are consistent with the presence of experimental uncertainties and unmodeled phenomena such as plate edge losses, or slight temperature sensor offsets.

This consistency between theoretical correlation, literature values, and observed data confirms that the chosen correlation structure is appropriate for modeling the thermal performance of the experimental PHE. Moreover, the narrow confidence interval for C_2 supports the robustness of the fitted model in capturing how changes in Reynolds number affect convective heat transfer across the trials.

EBD was used to evaluate data reliability by comparing heat gained by the cold stream to that lost by the hot stream. As shown in Fig. 2, most trials fell within ±30%, with 95% of all trials within ±54.91%. This indicates reasonable consistency for a lab-scale setup.

While some outliers suggest occasional unsteady conditions or heat loss to the environment, the symmetric spread of deviations implies random, rather than systematic, error. Since no trials were excluded from analysis, the dataset remains representative of real experimental variability.

Effectiveness and efficiency address distinct aspects of heat exchanger operation. *Effectiveness* measures how closely a system approaches the theoretical maximum heat transfer, often requiring knowledge of the capacity rate ratio and counterflow configuration—conditions not established in this experiment. As such, effectiveness could not be directly calculated.

Efficiency, in contrast, was estimated using the EBD. As shown in Fig. 2, the majority of trials maintained energy discrepancies within $\pm 30\%$, and 95% fell within $\pm 54.91\%$. This suggests that heat losses and experimental error were moderate, with most trials conserving more than 70% of thermal energy between inlet and outlet streams. Combined with the close agreement between U_{meas} and U_{calc} (Fig. 1), these results indicate that the system operated with sufficient consistency to support valid thermal performance conclusions.

The influence of flow rate on heat transfer was examined by isolating configurations with fixed hot-side or cold-side flow rates. As summarized in Tab. 2 and Tab. 3, increasing either flow rate generally increased U_{meas}, consistent with improved convection and higher Reynolds numbers.

Additionally, Fig. 3 plots U_{meas} against the flow rate ratio $\dot{m}_c/\dot{m}_h$. Within subsets of fixed flow conditions, U_{meas} scaled approximately linearly with flow ratio. This trend suggests that asymmetrical flow configurations; particularly those with increased cold-side flow, enhance convective performance by strengthening boundary layer disruption and increasing thermal driving force.

These observations support the model's predicted dependence on Reynolds number and highlight the practical importance of flow rate control in heat exchanger design.

Several factors may have contributed to variability in the data. Notably, the energy balance deviation (Fig. 2) revealed that some trials exhibited deviations exceeding 50%, suggesting potential heat loss to the surroundings, sensor inaccuracies, or incomplete system stabilization before measurements were taken. Additionally, small flow fluctuations and possible temperature reading lags may have influenced the calculated values of U_{meas}.

To improve future experiments, maintaining tighter control over steady-state conditions and recording multiple trials per flow configuration would enhance data reliability. Furthermore, exploring a broader range of flow rate combinations—especially under balanced conditions—could improve resolution of flow ratio effects. Repeating the experiment with different exchanger geometries or under counterflow conditions would also enable direct calculation of effectiveness and allow for more complete performance evaluation.

7 Conclusions

Nonlinear regression coefficients shown in Eq. (6) yielded values within the expected range of outcomes from literature, with $C_1 = 0.0856$ and $C_2 = 0.9370$, indicating turbulent flow within the compact plate heat exchanger. Additionally, a strong correlation was noted via Fig. 1 for measured heat transfer coefficients U_{meas} to their predicted values, U_{calc}, which suggests that the empirical Nusselt correlation is accurate. Additionally, the system reflected highly efficient heat transfer due to the strong correlation and trend shown between the predicted and measured heat transfer coefficients and the consistency of the energy conservation within the system, as shown in Fig. 2.

Future research and experiments should be conducted to verify and corroborate our findings; notably, only one trial for each combination of hot and cold flow was conducted, and steady state was not fully guaranteed for each data point. A wider range of temperature differences and flow rates (and larger comparative flow rate differences between cold and hot) could also be another avenue for research. Finally, examining the differences in types of plate heat exchangers (gasketed, brazed, and welded) and different geometries and apparatuses, like comparing counter-flow and cross-flow setups, and different liquids or plate metals could provide more insight into the governing equations, heat transfer coefficients, efficiency, and other aspects of plate heat exchangers.

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(7) Farraj, A. R.; Hrnjak, P. Experimentally Validated Correlations for Heat Transfer and Pressure Drop for Single-phase Flow in Frame-and-Plate Heat Exchanger. **2022**, Paper 2422.

(8) Song, M. et al. Experimental Investigation of the Heat Transfer Characteristics of Plate Heat Exchangers Using LiBr/Water as Working Fluid. *Energies* **2021**, *14*, 6761.

Appendix

GPM$_c$	**GPM**$_h$	**Flow Ratio**	$U_{\mathbf{meas}}$ **[W/m**^{2}**·K]**
1	1	1.000	7.86e+04
1	2	0.500	1.07e+05
1	3	0.333	1.32e+05
1	4	0.250	1.49e+05
1	5	0.200	1.66e+05
1	6	0.167	1.80e+05
1	7	0.143	1.98e+05
1	8	0.125	2.01e+05
1	9	0.111	2.14e+05

Table 2: Trials with fixed cold flow rate ($\dot{m}_c = 1$ GPM) and varied hot flow rates.

GPM$_c$	**GPM**$_h$	**Flow Ratio**	$U_{\mathbf{meas}}$ **[W/m**^{2}**·K]**
1	2	0.500	1.07e+05
2	2	1.000	1.58e+05
2	2	1.000	1.88e+05
3	2	1.500	2.36e+05
4	2	2.000	3.18e+05
5	2	2.500	4.03e+05
6	2	3.000	4.93e+05
7	2	3.500	5.41e+05
8	2	4.000	4.95e+05
9	2	4.500	6.03e+05
10	2	5.000	7.32e+05

Table 3: Trials with fixed hot flow rate ($\dot{m}_h = 2$ GPM) and varied cold flow rates.

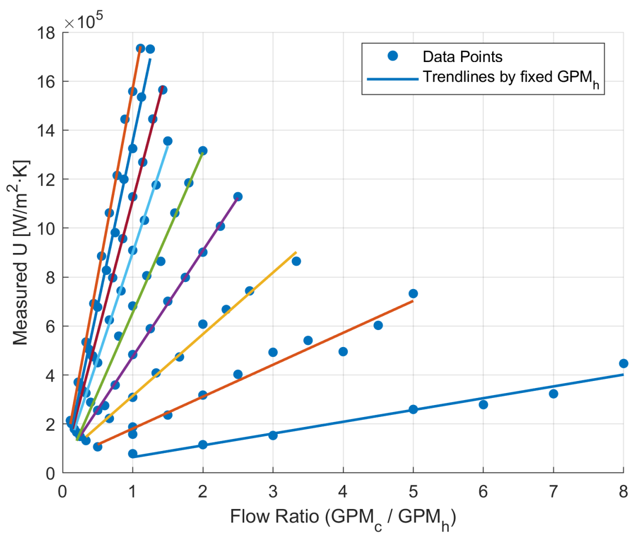

Figure 3: Measured overall heat transfer coefficient U_{meas} as a function of flow rate ratio $\dot{m}_c/\dot{m}_h$. Data points span multiple combinations of hot- and cold-side flow rates. Linear trendlines are added to highlight local trends among subsets with similar cold-side flow conditions.

1. Numerical study of shell and tube heat exchanger with different cross-section tubes and combined tubes

    - Author(s): Mohammad Reza Saffarian, Farivar Fazelpour, and Mehrzad Sham
    - Year published: 2019
    - Journal name: International Journal of Energy and Environmental Engineering
    - 1-3 major accomplishments of this paper:

        (a) Demonstrated that tubes near the outside of the shell in shell-and-tube heat exchangers have more impact on heat transfer than those near the center.

2. Thermal evaluation of nanofluids in heat exchangers

    - Author(s): Kanjirakat Anoop, Jonathan Cox, and Reza Sadr
    - Year published: 2013
    - Journal name: International Communications in Heat and Mass Transfer
    - 1-3 major accomplishments of this paper:

        (a) Showed that flow rate and nanofluid concentration in both shell-and-tube and plate heat exchangers have effects on augmentation and deterioration of the heat transfer coefficient

        (b) Suggested that nanofluids are limited in industrial applications due to a larger than expected pressure drop within the heat exchanger

3. Design and optimization of plate heat exchanger networks

    - Author(s): Kevin Xu and Robin Smith and Nan Zhang
    - Year published: 2017
    - Journal name: Computer Aided Chemical Engineering
    - 1-3 major accomplishments of this paper:

(a) Proposed an optimal design for two stream multi-pass plate heat exchangers (gasket and welded).

(b) Demonstrated a reduced heat transfer area compared to previously published models was similarly effective, and that the model works with the complext plate heat exchanger network.

4. Heat transfer correlations for single-phase flow in plate heat exchangers based on experimental data

- Author(s): Jie Yang, Anthony Jacobi, and Wei Liu
- Year published: 2017
- Journal name: Applied Thermal Engineering
- 1-3 major accomplishments of this paper:

(a) Experimentally investigated single-phase heat transfer for nine brazed plate heat exchangers with varying geometric parameters.

(b) Proposed individual and a generalized heat transfer correlation based on experimental.

5. Experiments and Correlations for Single-Phase Convective Heat Transfer in Brazed Plate Heat Exchange

- Author(s): M. A. Eldean, K. Sefiane, E. Alsusa, and D. Wen
- Year published: 2022
- Journal name: Journal of Heat Transfer
- 1-3 major accomplishments of this paper:

(a) Conducted experimental studies to determine single-phase convective heat transfer coefficients in a brazed plate heat exchanger.

(b) Developed or validated Nusselt number correlations for the specific PHE geometry and working fluids.

6. Experimental Investigation of the Heat Transfer Characteristics of Plate Heat Exchangers Using LiBr/Water as Working Fluid

   - Author(s): MinYoung Song, Seungmin Lee, Yongchan Kim, and Dongwoo Kim
   - Year published: 2021
   - Journal name: Energies
   - 1-3 major accomplishments of this paper:

     (a) Investigated the heat transfer performance of a plate heat exchanger specifically using Lithium Bromide/Water (LiBr/Water) solutions.

     (b) Analyzed the impact of LiBr/Water solution properties and operating conditions on heat transfer coefficients.

     (c) Contributed data and correlations relevant to absorption refrigeration and heat pump systems utilizing PHEs with LiBr/Water.

7. Experimentally Validated Correlations for Heat Transfer and Pressure Drop for Single-phase Flow in Frame-and-Plate Heat Exchanger

   - Author(s): Abdel Rahman Farraj and Pega Hrnjak
   - Year published: 2022
   - Journal name: Proceedings of the International Refrigeration and Air Conditioning Conference
   - 1-3 major accomplishments of this paper:

     (a) Presented experimental results for single-phase flow heat transfer and pressure drop in a frame-and-plate type heat exchanger.

    (b) Provided design data relevant to refrigeration and air conditioning applications employing frame-and-plate heat exchangers.

8. Review of Nusselt Number Correlation for Single Phase Fluid Flow through a Plate Heat Exchanger to Develop C# Code Application Software

    - Author(s): R. L. Pradhan, Dheepa Ravikumar, and D. L. Pradhan
    - Year published: 2013
    - Journal name: IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
    - 1-3 major accomplishments of this paper:
        (a) Reviewed a range of existing Nusselt number correlations for single-phase fluid flow in plate heat exchangers.
        (b) Discussed the methodology, including the modified Wilson plot technique, used to evaluate these correlations and determine convective heat transfer coefficients.