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# Theoretical and experimental analysis of dynamic heat exchanger: Retrofit configuration

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ABSTRACT

This paper theoretically and experimentally describes a dynamic plate heat exchanger configuration that decreases or even eliminates heat exchanger losses in performance and efficiency associated with transient flow rates of hot and cold streams passing through its interior or other sources of imbalance. Heat exchanger constraints are some of the most restrictive transient response constraints in a process and thereby inhibit the process's agility and responsiveness. These constraints include temperature changes, expansion, or thermal stresses in the heat exchangers or neighboring process equipment. Despite any changes in inlet conditions, the proposed configuration is capable of leveling the varying parameters such that the exit temperatures remain fixed. Theoretical and experimental results show that the proposed configuration can respond to changes in process flow rates with a near-zero time constant.


## 1. Introduction

PHE (plate heat exchangers) are becoming increasingly applicable because of their efficient and compact design. They serve as key components for various processes in industry, including the food processing, pharmaceutical, dairy, chemical and petrochemical industries. Aminian et al. [1] reported on a PHE that weighed 95% less than a comparable shell-and-tube exchanger and still provided 300–400 square feet of surface for heat exchange per cubic foot of volume. Many processes involve scheduled changes in load or other process conditions but experience unscheduled ones as well. The heat exchangers of a process are commonly the most sensitive components to such changes.

Heat exchangers react in a non-linear way with changes in inlet properties, making them difficult to control effectively. Therefore, sophisticated models are used to prominently predict the steady-state and transient performance of different heat exchanger designs [2,3]. Current commercial software can design heat exchangers and accurately evaluate their performance. However, these models do not commonly provide optimization solutions [4,5]. Heat exchanger design typically involves specifying the inlet temperatures and flow rates as well as the target hot and cold fluid outlet temperatures. The figures of merit include efficiency, heat exchanger size, and flow resistance. The optimization of plate heat exchangers involves manipulating a large number of design variables, some of which are inherently discrete, causing the task to be non-trivial [6–8].

Thermodynamic irreversibility in a heat exchanger comes from the transfer of heat across a finite temperature difference between the hot and cold streams. Based on this concept, the optimization of a heat exchanger is equivalent to minimizing the amount of useful power that is lost [9–12]. Mishra et al. [13] used a genetic-algorithm-based optimization technique on a cross-flow plate and fin heat exchanger to minimize the entropy generation while maintaining a constant heat duty. Cheng [14] introduced the concept of entropy resistance which uses entropy generation analysis as an alternative method for heat exchanger analysis. Fakheri [15] used the second law of thermodynamics to calculate the thermal efficiency of a heat exchanger as the ratio of the actual heat transfer rate to the optimum heat transfer rate. Fakheri [16]

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also extended this concept to determine the efficiency of heat exchanger networks excluding the need for charts, or complicated performance statements.

There are several studies addressing the issue of liquid temperature control in heat exchangers. Luyben [17] studied the issues of heat exchanger bypass control. Almutairi and Zribi [18] explored the applications of three different TSM (terminal sliding mode) controllers to a plate heat exchanger. Gonzalez et al. [19] presented a MPC (model predictive control) for a network of heat exchangers. Bonivento et al. [20] compared the performance of a standard PID controller with a generalized predictive control. Ramirez et al. [21] incorporated the MMMPC (min–max model predictive control) for an industrial heat exchanger. Additional applications of MPC to heat exchangers can be found elsewhere [22–26].

Artificial intelligent control schemes such as ANN (artificial neural network) and fuzzy logic systems have been extensively applied for the thermal control of heat exchanger structures. Jian et al. [27] presented an adaptive fuzzy sliding mode controller for the temperature control of heat exchangers. Skrjanc and Matco [28] proposed a new predictive control structure based on a nonlinear fuzzy model. Ramirez et al. [29] explored the application of neural network technique for the min–max predictive control of a heat exchanger. Further studies in the area of heat exchanger control based on neural network method appear elsewhere in the literature [30–33].

Changes in the opposite fluid flow rate or temperature control the fluid temperatures in all the above-mentioned investigations. Flow rate changes may cause the flow regime to shift from laminar to turbulent, significantly decreasing the heat transfer coefficient. To address this issue, a minimum bound should be imposed on the input flowrate, and the controller should be retuned each time the flowrate changes, which is a challenging task. Although manipulating the opposite fluid inlet temperature guarantees a turbulent hydrodynamic regime inside the exchanger, it suffers from a time delay [34,35].

The device described in this document, however, exhibits a heat exchanger technology that significantly reduces or eliminates compromises in heat exchanger outlet temperatures and performance associated with transient process perturbations without changing the thermal power at the inlet of the opposite stream. Furthermore, the presented technology responds to changes in process transients with a very short-lived transients in the exiting flows, which minimizes thermal stress in the heat exchanger during process changes.

The majority of design in engineering focuses on the performance of steady-state processes. In this work, steady-state analysis is expanded upon to include detailed transient behaviors. The objective of the work is to aid the development of agile energy-storage systems and load-following processes, which are both transient in nature. Transient analyses regularly identify heat exchangers as the unit operations that are most vulnerable and sensitive to fluctuations in process conditions. During transient moments, heat exchanger performance often undermines process safety, product quality, environmental threat, and equipment reliability. Reliability threats stem from both materials constraints inside the heat exchanger and from downstream ramifications of streams that fail to meet their design conditions.

The energy storage and process load following that inspire this work are only two of several applications that profit from transient analyses. Transient analyses point out process susceptibilities to load changes, upsets, control complexity, and broad responses prompted by local changes in densely integrated systems. The solutions proposed and exhibited in this research greatly decrease and even eliminate these process susceptibilities, at least with regards to heat exchangers. Specifically, these procedures simplify controls, conserve process set points during transients, confine process upsets, and decrease process variable cycling. This work's motivation is to describe a dynamic heat exchanger that will eliminate the exchanger efficiency and performance losses that originate from the transient flow rates of entering streams. The discussion here presumes a heat exchanger that is initially balanced, that is, initially has approximately equal values of $\dot{m}c_p$ in each direction. The methods described here can also prevent further efficiency losses in an imbalanced heat exchanger if it experiences a flow perturbation that further imbalances it. However, flow perturbations that tend to balance it will improve its efficiency and generally would not benefit from this technology.

### 1.1. Background

Fig. 1 shows a common, countercurrent, two-stream heat exchanger that could be of any design, i.e. brazed-plate, plate-and-frame, or shell-and-tube. Hot and cold streams enter the exchanger on the left and right sides, respectively, and exchange heat such that the temperature of the hot stream decreases while that of the cold stream increases. The outlet temperature of the cold stream often exceeds that of the hot stream, leading to possible confusion about which stream is the hot or cold stream. In this discussion, hot and cold classifications accompany the inlet temperatures, as is most common in practice and as shown in the figure. In this discussion, the outlet temperature of the cold stream is commonly higher than that of the hot stream.

Many industries use multi-stream heat exchangers in which more than two streams enter and exit at different positions along the heat exchanger. Industries that prioritize heat integration commonly use multi-stream heat exchangers, e.g., the cryogenic processing industry [36–39]. The analyses demonstrated here also apply to multi-stream systems assuming the hot and cold streams are regarded as the mass-flow-weighted average properties of all hot and cold streams.

### 1.2. Heat exchanger efficiency

The technical literature does not define a heat exchanger efficiency. This document suggests one such useful definition. Insulated heat exchangers conserve enthalpy, so a first-law definition is problematic. That is, the enthalpy flowing out of the system equals that flowing in. Heat exchangers do not involve shaft work, so a second-law definition (work over heat) does not naturally come to mind. Nevertheless, this document proposes a second-law definition for heat exchanger efficiency that is both useful and simple.

Conceptually, this efficiency describes the consequence of heat exchange on the flow streams' (a) ability to do work (availability or exergy) or, equivalently, (b) entropy. Quantitatively, the heat exchanger efficiency is one minus the difference in exergy between the streams exiting and entering a heat exchanger normalized by the largest achievable difference in such exergy. The largest achievable difference with respect to heat exchange occurs if all the streams come to the same temperature. These analyses and this definition assume no heat transfer between the exchanger and its

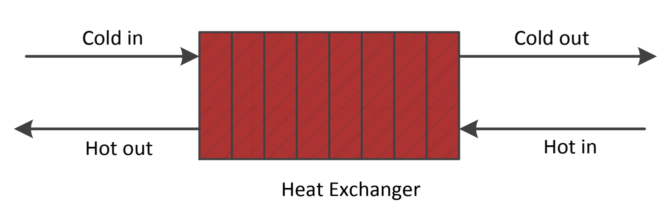


**Fig. 1.** Schematic diagram of a typical two-stream, counter-current heat exchanger.