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A novel Heat Exchanger Network Bridge Retrofit method using the Modified Energy Transfer Diagram

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ABSTRACT

The aim of this paper is to develop a novel method for the retrofit of Heat Exchanger Networks based on Bridge Retrofit analysis. The method identifies Retrofit Bridges that correspond to energy saving modifications using two new proposed tools: The Heat Surplus-Deficit Table and the Modified Energy Transfer Diagram. These tools both allow the identification and quantification of Retrofit Bridges. These tools have been developed following conventional Pinch Analysis tools such as the Composite Curve and Grand Composite Curve. The connection between the conventional Heat Exchanger Network synthesis tools and the proposed retrofit tools is established to improve understanding of the method and relate it to what is currently used in both literature and industry. The method is demonstrated with a simple illustrative example and a more detail paper mill case study. The paper mill incorporates a paper machine and paper recycling plant and is co-located with a Kraft pulp mill in New Zealand. Results from the retrofit method suggest a retrofit design that will achieve an annualised profit of NZD 570,000/y (USD 414,000/y) with a payback of 2.4 y.

1. Introduction

Increasing global focus on energy generation and consumption as well as its cost, sustainability, and environmental impacts, have provided the industrial sector with a strong incentive to look for opportunities for process improvement [1] and process sustainability through renewable energy [2]. Process improvement can be achieved through Process Integration to reduce energy consumption and environmental impacts for the same production and/or through debottlenecking to increase production using the same equipment and lower specific energy consumption [3]. A key pathway to improve Process Integration is through the retrofit of the Heat Exchanger Network (HEN) [4]. The subject of this paper focuses on HEN retrofit.

There are three general approaches to deciding how to retrofit a HEN [5]: (1) Pinch Analysis (PA)-based graphical procedures, (2) Mathematical Programming (MP) through the formulation of a retrofit superstructure and its optimisation, and (3) a combination of both graphical and Mathematical Programming techniques. PA techniques rely on thermodynamics to express the potential retrofit heat savings for a HEN using graphs. Inherent with these procedures is a high degree of input from the engineer, which helps lead to practical solutions that meet all the requirements of the considered process and site. Graphical approaches often double as effective communication tools to walk industrial engineers through the process from which a solution is derived. The disadvantage of PA techniques is the "optimal" solution will rarely be obtained. MP, on the other hand, seeks to find the global optimal solution given a set of variables, superstructure relationships, and constraints. Besides the model formulation, there is minimal opportunity for input by the engineer. Most Mathematical Programming models for both inputs and outputs are often displayed from a command line, creating a key barrier to the communication of the ideas with industry. This work continues a recent resurgence in the development of graphical PA techniques for HEN retrofit.

PA encompasses well-known tools such as Composite Curves (CC) and Grand Composite Curves (GCC) [6] that also lead to Total Site Heat Integration tools such as Total Site Profiles and Site Utility Grand Composite Curves [7]. These sets of tools have been effectively applied to address the problem of individual process and

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Nomenclature

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A	Area (m^2)
ACC	Annualised Capital Cost (NZD/y)
b	Capital cost proportional constant (NZD/m^2)
CI	Capital Investment (NZD)
CP	Specific Heat Capacity Flow Rate (kW/°C)
f	Fixed investment cost (NZD)
H	Enthalpy (kW)
H*	Superimposed Enthalpy Cascade (kW)
LF	Lang Factor
n	Capital cost exponent
PB	Simple Payback Period (y)
Q	Exchanger Duty (kW)
S	Utility Savings (NZD/y)
T	Temperature (°C)
T*	Shifted Temperature (°C)
TRP	Total Retrofit Profit (NZD/y)
UC	Utility Cost (NZD/y)

Greek

Δ	difference between two states

Subscripts

cont	contribution
c	cold
h	hot
min	minimum

Abbreviations

C#	Cooler
CC	Composite Curves
E#	Exchanger
E-PTA	Exchanger Problem Table Algorithm
EGCC	Exchanger Grand Composite Curve
ETD	Energy Transfer Diagram
GCC	Grand Composite Curve
H#	Heater
HEN	Heat Exchanger Network
HSDT	Heat Surplus-Deficit Table
HTE	Heat Transfer Enhancement
MER	Maximum Energy Recovery
METD	Modified Energy Transfer Diagram
N#	New Exchanger
PA	Pinch Analysis
SCC	Shifted Composite Curve

Total Site integration and provide an avenue to convince the industrial end-user to adopt the solution. As a result, PA and Total Site Heat Integration have successfully been applied to define how new chemical and processing plants and sites can increase overall energy efficiency and environmental performance. However, the insights from PA and Total Site Heat Integration are often aggregated across an entire process or site such that the fidelity of a retrofit problem, including the design of the current HEN, is lost.

Many recent studies have sought to develop HEN retrofit methods that maximise energy savings through improved design. Smith et al. [8] reviewed and extended the Network Pinch retrofit method to provide a coherent step-wise design strategy to move from an existing level of integration towards maximum energy recovery in a sequence of steps. Ochoa-Estopier et al. [9] undertook a comprehensive three-part industrial case study that combined both process models of a Crude-oil Distillation system [9] and HEN retrofit method and model [10] into a single optimisation framework [11] to generate a highly integrated, low energy solution. Realizing that adding new exchangers or repiping existing ones are often costly, Jiang et al. [12] focused on increasing energy savings for a fixed network structure developing sensitivity curves to predict how increases in heat exchanger area may provide utility reduction. This was followed by Akpomiemie and Smith [13] who undertook greater depth of heat exchanger modelling in conjunction with the installation of Heat Transfer Enhancement (HTE) to identify the increase in the duty of critical heat exchangers. Next, Pan et al. [14] added pressure drop constraints and fouling mitigation potential into the retrofit analysis of using HTE in a fixed HEN structure. Akpomiemie and Smith [15] combined their team's recent efforts on both structural and enhancement type retrofit methods to comprise an overall cost-effective strategy to increase energy efficiency. Ayotte-Sauvé et al. [16] applied a Mixed Integer Nonlinear Programming technique to solve a retrofit superstructure using a step-wise approach with the possibility of user intervention after each step.

The challenge of developing new PA-based tools that use thermodynamics to express the current HEN and potential retrofit modifications has been recognised in several recent papers. Recent examples include the development of Advanced Composite Curves [17], the extension of the Stream Temperature versus Enthalpy Plot to HEN retrofit [18], new Temperature Driving Force Curves [19], an extended Network Pinch method [20], a Shifted Retrofit Thermodynamic Grid Diagram [21], and Bridge Analysis based on the new Energy Transfer Diagram [22]. Each of these approaches deserves further consideration and development with the selected focus of this paper being to extend the Energy Transfer Diagram. Bonhivers et al. [22] recognised the need to develop a new retrofit tool that synthesised the HEN with the background process. The new tool was the Energy Transfer Diagram (ETD). In addition, Bonhivers et al. [23] explained a set of concepts related to the ETD with emphasis on the advantage of a Retrofit Bridge over a Path Retrofit. The ETD provides a visual and numerical expression of each individual component of a HEN and its potential to be reintegrated more efficiently. The heat exchanger pockets that comprise the ETD show where heat is transferred across the Pinch, which heat exchangers have excessive temperature driving forces that can be better exploited, and target the potential for retrofit. Combined with these efforts, a new retrofit method based on the ETD was developed called Bridge Analysis. Similar to the conventional Pinch-based Loops and Paths retrofit method [24], Bridge Analysis aims to find energy savings pathways between cold and hot utility use. However, these pathways are not constrained to the present structure of the HEN, which provides a key advantage in that all combinations of bridges including those attained by structural HEN modification can be found [22]. Later, Bonhivers et al. [25] took the concept a step further to develop a heat exchanger load diagram followed by a hybrid CC and ETD plot [26].

In the four years since publication, Bridge Analysis and the ETD has not received much attention beyond Bonhivers and co. At present, there are three published case studies using the technique: (1) Bonhivers et al. [25] for a Kraft pulp mill, (2) Jahromi and Beheshti [27] for a methanol-to-propylene plant, and (3) Chen et al. [28] with the optimisation of a single-effect ammonia-water absorption system. Despite its usefulness and validity, its