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Locating exchangers in an EIP-wide heat integration network

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ABSTRACT

Inter-plant heat integration offers an energy-saving opportunity in eco-industrial parks (EIPs) beyond the traditional intra-plant integration. The economic feasibility of this integration depends critically on the locations of heat exchangers. In this work, we generalize our previous study on centralized HENS (Heat Exchanger Network Synthesis) for EIPs to allow exchangers to be located at either plant or central sites facilitating both intra-plant and inter-plant heat integration in a seamless manner. We propose a mixed integer non-linear programming (MINLP) model that synthesizes a maximum-NPV (Net Present Value) EIP-wide HEN, while accounting for all the capital (e.g. heat exchangers, pumps, and pipelines) and operating (pumping costs, utility savings) cash flows along with the ambient heat gains/losses during transports. The model is tested on five examples from the literature and gives better HENs compared to the previous results. This work highlights and quantifies the impact of heat exchanger locations in an EIP-wide HEN.

1. Introduction

The world's population is growing and projected to increase from 6.51 billion in 2005 to 7.79–10.76 billion in 2050 (Nehring, 2009). Fossil fuels, the main source of energy in the world, are depleting and causing global warming. These concerns are encouraging global efforts for energy efficiency and conservation. Heat integration is a well-established technique for energy conservation in the chemical industry. The heating/cooling demands of streams in a plant can be synergized to gain economic and environmental benefits. This strategy can also be applied to a community or complex of closely located plants, called an Eco-Industrial Park (EIP) (Tudor et al., 2007), to gain environmental, economic, and societal benefits through collaboration (Manahan, 2004). The collaboration reduces the net consumption of energy, raw materials, water, and other resources. Some successful EIPs are Kashima Industrial park in Japan, Jurong Island in Singapore, London Remade eco-industrial sites in the United Kingdom, Ecosite du Pays de Thau in France (Gibbs et al., 2005; Matsuda et al., 2009).

Interplant heat integration poses unique challenges such as locating exchangers, transporting streams, terms and conditions of collaboration, and interdependence of plants (Chen and Lin, 2012; Nair et al., 2016). Hui and Ahmad (1994) developed a nine-step procedure based on pinch analysis for inter-plant HEN. Instead of using explicit plant-to-plant distances, they assigned a fixed investment for all plant-to-plant connections. Bagajewicz and Rodera (2000) used LP (Linear Programming) and MILP (Mixed Integer Linear Programming) models to integrate four plants, but ignored the critical reality of plant-to-plant distances, transport costs, and investment for pumps and pipelines. Laukkanen et al. (2012) developed a model for both direct and indirect heat integration among processes. They assumed that the fixed costs of the exchangers included the piping costs, which is rather simplistic. Hiete et al. (2012) used pinch analysis to heat integrate four plants, but did not report any HEN. Cheng et al. (2014) proposed a game-theoretic strategy where a plant can "trade" a stream with another plant for heat integration. However, like Bagajewicz and Rodera (2000), Cheng et al. (2014) also ignored locations, transports, and investments. Wang et al. (2015) proposed a combined direct/indirect heat integration for two plants. They considered piping costs, but neglected pumps and pumping costs. Nemet et al. (2016) considered the key issues of pipeline design, heat losses, and pressure drops, while designing a direct/indirect heat integration network. However, their models were either too complex or not designed to handle more than two plants.

None of the above interplant heat integration efforts addressed the issue of exchanger locations. Heat exchanger locations in an EIP-based network are critical, as they affect the piping and pumping costs and ambient heat losses/gains. Nair et al. (2016) proposed the idea

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Nomenclature

Subscripts

e	Enterprise in an EIP
i	Hot process stream
j	Cold process stream
p	Plant
k	Stage in the HEN superstructure
s	Process stream

Superscripts

L	Lower limit
U	Upper limit

Parameters

COE	Cost of electricity ($/W)
CPL	Installed pipe cost per unit length ($/m)
dd	Distance between plants (m)
E	Number of enterprises
F	Heat-content flow (mass flow × heat capacity or kW/K) of hot stream
FCH	Fixed component of the purchase cost of a heat exchanger ($)
FCP	Fixed component of the purchase cost of a pump ($)
G	Heat-content flow (mass flow × heat capacity or kW/K) of cold stream
I	Number of hot process streams
J	Number of cold process streams
K	Number of stages in the superstructure excluding the utility exchanger stages
MH	Installed cost-purchased cost multiplier for an exchanger
MP	Installed cost-purchased cost multiplier for a pump
MTA	Minimum allowable temperature approach in an exchanger (K)
N	Number of years
P	Total number of plants
r	Interest rate for NPV computation
S	Number of process streams
SS	Number of substreams in a stage
TIN	Initial temperature of stream (K)
$TOUT$	Final (target) temperature of stream (K)
U	Overall heat transfer coefficient (kW/m^2-K)
UC	Unit utility cost ($/kW-a)
VCH	Coefficient in the variable component of the purchase cost of a heat exchanger
VCP	Coefficient in the variable component of the purchase cost of a pump
VF	Volumetric flow rate (m^3/a)
α	Exponent in the cost correlation for a pump
β	Exponent in the cost correlation for an exchanger
Δp^{HE}	Pressure drop per exchanger (Pa)
Δp^{L}	Pressure drop per unit length (Pa/m)
ΔT	Average temperature rise per unit distance (K/m)
η	Pump efficiency
ρ	Density (kg/m^3)

Continuous variables

A	Area of an exchanger (m^2)
$CAPEX$	Total capital expense ($)
CP	Purchase cost of pump ($)
CTA	Temperature approach at the cold end of an exchanger (K)
D	Temperature change for hot substream in an exchanger (K)
EP	Pump power (W)
f	Fractional heat-content flow of hot substream in an exchanger
g	Fractional heat-content flow of cold substream in an exchanger
HEC	Heat exchanger cost ($)
HTA	Temperature approach at the hot end of an exchanger (K)
LPL	Length of pipeline (m)
$LMTD$	Logarithmic mean temperature difference (K)
NPV	Net present value ($)
$OPEX$	Operating expense ($/a)