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Indirect heat integration across plants using hot water circles☆

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ABSTRACT

Total site heat integration (TSHI) provides more opportunities for energy saving in industry clusters. Some design methods including direct integration using process streams and indirect integration using intermediate-fluid circuits, *i.e.*, steam, dowtherms and hot water, have been proposed during last few decades. Indirect heat integration is preferred when the heat sources and sinks are separated in independent plants with rather long distance. This improves energy efficiency by adaption of intermediate fluid circle which acts as a utility provider for plants in a symbiotic network. However, there are some significant factors ignored in conventional TSHI, *i.e.* the investment of pipeline, cost of pumping and heat loss. These factors simultaneously determine the possibility and performance of heat integration. This work presents a new methodology for indirect heat integration in low temperature range using hot water circuit as intermediate-fluid medium. The new methodology enables the targeting of indirect heat integration across plants considering the factors mentioned earlier. An MINLP model with economic objective is established and solved. The optimization results give the mass flow rate of intermediate-fluid, diameter of pipeline, the temperature of the circuits and the matches of heat exchanger networks (HENS) automatically. Finally, the application of this proposed methodology is illustrated with a case study.

1. Introduction

In recent years, increasing consumption of fossil fuels has gained growing concerns about energy efficiency all around the world [1,2]. To mitigate the future climate challenges and rising fuel price risks, most industries are seeking strategies to reduce energy efficiency. Actually, energy efficiency can be significantly enhanced by better heat recovery technologies. Those approaches are seen as sustainable solutions for industries and are expected to improve energy efficiency at economical cost.

Many methods and concepts had been explored to optimize energy systems in chemical processes. Pinch technology was first developed by Linnhoff as an applicable design method for HENS in an individual process [3,4]. Dhole and Linnhoff extended pinch technology into TSHI for fuel co-generation, emissions, and cooling [5]. In their work, only different levels of steam were used as the intermediate to accomplish indirect heat integration between processes. TSHI had received growing interests since 1990s. It allows industrial clusters to accommodate heating and cooling demands of different processes in an overall perspective [6–8]. Ahmad and Hui studied both indirect heat integration using different levels of steam and direct heat integration using processes streams [9]. Hui and Ahmad continued their work by integrating energy and capital calculations [10]. Another continuous work was done by Hui and Ahmad, and only indirectly heat integration using different levels of steam was considered between different processes [11]. Their studies were all based on graphical targeting tools of pinch technology.

Bagajewicz and Rodera found that a single plant can further improve energy efficiency by sharing energy with other plants [12]. They developed an energy targeting procedure for heat integration between two plants. Based on mathematical programming, they studied direct heat integration using processes streams and indirect heat integration using intermediate-fluid circuits which needed not to be isothermal. Bagajewicz and Rodera developed another procedure for heat integration across plants using intermediate-fluid circle and calculated targets for several industrial cases [13]. They also developed an MILP model to determine the optimal location of the fluid circuits in indirect heat integration. Bagajewicz and Rodera extended their work for systems with more than two plants [14]. They pointed out that direct integration may achieve less energy savings than indirect integration, as there would be a large heat loss for process streams participated in heat transfer across plants especially when the distance was long. Thus, indirect heat integration between independent plants using transfer mediate was preferred [15]. Hackl and Andersson analyzed the synergy effects of cooperation between different plants [16–18]. In their work, they suggested hot water circles to build a more interconnected utility system. This enables heat integration between plants in order to achieve

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an industrial symbiosis and decrease resource energy consumption. No energy-capital trade-off calculations were carried out in their studies.

Most researches above only consider heat recovery aspects. However, Wang and Feng found that distance was also a key factor which was not fully considered in conventional TSHI [15]. Firstly, heat loss results in a large decline in the heat quality during long distance transportation, so that the temperature of intermediate-fluid might not be high enough to satisfy the heat sinks. Secondly, the investment of pipeline, cost of pumps and additional heat exchangers was very high, especially when the distance between plants is long. Thirdly, the pump power for transporting fluid during transportation should be considered. Nevertheless, their studies only simulated the TSIH with considering distance factors. The mass flow rate and temperature of intermediate-fluid circuit were not optimized, which have a significant impact on the economic aspect of TSIH.

This work presents a mathematical programming approach for indirect heat integration across plants considering the factors mentioned. As the work focus on low temperature range, hot water is used as the intermediate-fluid medium. An MINLP model based on economic objective is established and solved. The optimization can give the mass flow rate of intermediate-fluid, diameter of pipeline, the temperature of the intermediate-fluid circuits and the matches of HENS automatically. The proposed methodology can be used by industrial clusters to explore energy and cost savings opportunities. The application is illustrated with a case study based on two plants within an industry cluster.

2. Methodology

This section presents a systematic methodology to target maximum waste heat recovery in low temperature range across individual plants within one industrial cluster. Economical intermediate-fluid circuit between independent plants can be established to accomplish indirect heat integration synergies. The methodology consists of several steps below.

2.1. Definition

A plant is defined as an independent production unit which consists of one or more processes served by a utility system [19]. There is a large amount of excess heat ejected to cold utility in some plants. Meanwhile, some cold streams are located in other plants. Sharing and use of waste heat between these plants show significant energy savings. As the distance is long, indirectly heat integration between these plants using intermediate-fluid circuit is considered. For the purposes of developing the problem statement, the heat source and sink plant are additionally defined as follows.

(1) Heat source plant is characterized with excess heat by several hot steams, where it is allowable for pipeline's series and parallel between each stream.
(2) Heat sinks plant is characterized with several cold steams, where it is allowable for pipeline's series and parallel between each stream.

It is noted that when it is a two-plant heat integration problem, the two plants are a pure heat sink plant and a pure heat source plant respectively. When the problem consists of more than two plants, some of plants in the problem can be a heat sink plant and a heat source plant at the same time.

2.2. Superstructure of the MINLP model

Floudas *et al.* have established an MINLP model of heat exchange between one cold stream and many hot streams or one hot stream and many cold streams [20]. In their work, a procedure is presented for automatic generation of optimal configurations for HENS. The superstructure in Fig. 1 [20] includes alternatives for splitting, mixing and bypass of stream, where streams can be mixed non-isothermally to increase the amount of heat recovery with minimal heat transfer area. Heat integration between plants using intermediate-fluid circuits can be seen as heat exchange between one cold stream and many hot streams or one hot stream and many cold streams. This superstructure also includes options for series and parallel matching as well as splitting, mixing and bypassing between streams.

2.3. Objective and related constraints

Some key factors should be optimized, *i.e.*, the mass flow rate, supply and return temperatures of the intermediate-fluid circuit, and the matches between the intermediate-fluid and process streams.

2.3.1. The overall economic objective

The proposed economic objective is defined as follow:

$$\min\ TAC = \sum_{i\in IH} C_{CU}\cdot Qtr_i + \sum_{p\in PC} C_{HU}\cdot Qtk_p + Pumping + A_f\cdot\left(\sum_{i\in IH} CostHer_i + \sum_{p\in PC} CostHek_p + Costpipe + Costpump\right) \quad (1)$$

where C_{CU} and C_{HU} are the price of the cold and hot utilities respectively, Qtr_i and Qtk_p are the load of cold and hot utilities located over the hot and cold streams of i and p respectively. $CostHer_i$ and $CostHek_p$ are the capital costs of additional exchangers in sources plant and sinks plant, respectively. *Pumping* is the operation cost of pumps and *Costpump* is the capital cost of pumps. *Costpipe* is the capital cost of the pipeline. In the above relation, A_f is the annual factor of cost which is calculated as follows:

$$A_f = \frac{I\cdot(1+I)^n}{(1+I)^n-1} \quad (2)$$

where, n is the lifetime of the exchanger in term of year and I is the annual interest rate.

2.3.2. Constraints

The hot water circuit between plants is showed in Fig. 2. The mathematical model for indirect heat integration synthesis includes all possible connections. Notation used in the formulation is indicated as below.

IH {i:i is a hot stream}
PC {p:p is a cold stream}
Mar_i, Mak_p the mass flow rate of water from $split_r$ and $split_k$
Mbr_i, Mbk_p the mass flow rate of water from Mix_i and Mix_p
$Mcr_{i,j}$, $Mcr_{p,q}$ the mass flow rate of water from $split_i$ and $split_p$ to Mix_i and Mix_p
$Mcr_{i,j}$, $Mck_{r,q}$ the mass flow rate of water from $split_i$ and $split_r$ to Mix_j and Mix_q
$Tinr_i$, $Tink_p$ the temperature of water from Mix_i and Mix_p to exchanger i and p
$Toutr_i$, $Toutk_p$ the temperature of water from exchanger i and p
Ybr_i, Ybk_p binary variables which define the existence of additional heat exchangers i and p.

Constraints for splitters:

$$M = \sum_{i\in IH} Mar_i, \forall i\in IH \quad (3)$$

$$M = \sum_{p\in PC} Mak_p, \forall p\in PC \quad (4)$$