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An efficient optimization algorithm for waste Heat Integration using a heat recovery loop between two plants

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HIGHLIGHTS

- Convex reformulation and piecewise wise relaxation are used to reduce the computational efforts.
- Connection cost and pump related cost are involved.
- Industrial scale problem can be solved efficiently.
- Lower total cost can be obtained.

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ABSTRACT

Heat recovery loop (HRL) is an indirect approach for waste Heat Integration between plants. The mathematical model for HRL design is a complex and nonlinear problem, which results in a non-convex Mixed Integer Nonlinear Programming (MINLP) model. Solving the problem without any strategy is difficult since computational results can easily be trapped in the local optimum solutions. This is mainly due to the reasons that operation cost, capital cost of heat exchanger networks, piping and pumping cost are considered simultaneously. To overcome this limitation, an efficient optimization algorithm is proposed for the complex problem. With application of convex reformulation and piecewise wise relaxation, the problem can be reformulated as a convex MINLP model, in which the objective function is convex and all constraints are linear. The computational efforts are reduced largely and better solutions can be obtained for the HRL design. As this work concentrates on low grade heat recovery, hot water is selected as the intermediate fluid to achieve waste Heat Integration between plants. An industrial case is demonstrated to illustrate the effectiveness of the proposed algorithm.

1. Introduction

Nowadays, the depletion of fossil fuel reserves and increasing concerns on carbon emission attract serious attention all over the world. Various basic materials plants like chemical, petrochemicals and other industrial clusters are seeking sustainable strategies for this global challenge [1]. It is well known that the energy efficiency in a single plant can be further improved by sharing energy with other plants, which is also called as waste Heat Integration between plants. This energy conservation approach has received growing interest since its inception in 90s of last century [2].

Early attempt about Heat Integration between individual plants was initiated by Linnhoff and Eastwood [3]. Based on Pinch Technology, they established energy targets for waste Heat Integration between plants. Further on, Klemeš et al. [4] studied Total Site Heat Integration, which showed that energy saving could be accomplished using the centralized utility system [5]. By studying both direct and indirect Heat Integration, Ahmad and Hui [6,7] reported that direct integration across plants was not always practical. This is mainly due to the operational issues and so the common utility system is widely used to achieve the indirect integration between plants [8]. While twice heat transfers reduce the temperature driving forces, indirect integration is often practical and easier to be governed or maintained [9]. Most of the studies about Total Site Heat Integration are mainly about heat recovery in high temperature range and steam is selected as the intermediate fluid [10,11]. However, steam transfers latent heat at fixed temperatures and some integration opportunities in certain case can be missed. Steam also cannot be applied to recovery waste heat in low temperature range. So some researchers suggest thermal oil or hot water as the intermediate fluid to transfer sensible heat between plants [12].

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Nomenclature

Sets and indices
- HP set of hot streams
- CP set of cold streams
- i hot stream in the source plant
- j cold stream in the sink plant
- kh the superstructure stage in the source plant
- kc the superstructure stage in the sink plant

Parameters
- NH number of hot streams in the source plant
- NC number of cold streams in the sink plant
- Ccu utility cost coefficient for all hot streams, \$/(kW y)
- Chu utility cost coefficient for all cold stream, \$/(kW y)
- cp specific heat capacity of intermediate fluid, kJ/(°C kg)
- Fh_i heat capacity flow rate of hot stream i in the source plant, kW/°C
- Fc_j heat capacity flow rate of cold stream j in the sink plant, kW/°C
- h_i heat transfer coefficient of hot stream i in the source plant, kW/(°C m^2)
- h_j heat transfer coefficient of cold stream j in the sink plant, kW/(°C m^2)
- hw heat transfer coefficient of the intermediate fluid
- Hy total time for operation, h
- L distance between the source and sink plants, m
- Pe price of electric, \$/(kW h)
- $Thin_i$ initial temperature of hot stream i in the source plant, °C
- $Thout_i$ final temperature of hot stream i in the source plant, °C
- $Tcin_j$ initial temperature of cold stream j in the sink plant, °C
- $Tcout_j$ final temperature of cold stream j in the sink plant, °C
- Ω_i total heat load of hot stream i in plant, kW
- Ω_j total heat load of the cold stream j in plant, kW
- Γh_i upper bound for temperature difference for stream i in source plant, °C
- Γc_j upper bound for temperature difference for stream j in sink plant, °C
- ρ density of the intermediate fluid, kg/(m^3)
- I fractional interest rate per year
- n number of years of operation

Continuous variables
- M mass flow of the intermediate fluid stream
- $th_{i,kh}$ temperature of hot stream i at hot end of stage kh in the source plant
- thm_{kh} temperature of cold intermediate fluid stream at cold end of stage kh in the source plant
- $tc_{j,kc}$ temperature of cold stream j at cold end of stage kc in the sink plant
- tcm_{kc} temperature of hot intermediate fluid stream at hot end of stage kc in the sink plant
- $thmin$ inlet temperature of intermediate fluid stream in the source plant
- $thmout$ outlet temperature of intermediate fluid stream in the source plant
- $tcmin$ inlet temperature of cold intermediate fluid stream in the sink plant
- $tcmout$ outlet temperature of cold intermediate fluid stream in the sink plant
- $qh_{i,kh}$ heat load between the intermediate fluid and hot stream i at stage kh in the source plant
- $qc_{j,kc}$ heat load between the intermediate fluid and cold stream j at stage kc in the sink plant
- $dth_{i,kh}$ temperature difference between the intermediate fluid and hot stream i at stage kh
- $dtc_{j,kc}$ temperature difference between the intermediate fluid and cold stream j at stage kc
- $\Delta Tmin$ minimum temperature difference for all heat exchangers
- η the efficiency of pump
- TAC total annual cost
- $qc_{j,kc}$ heat load between the intermediate fluid and cold stream j at stage kc in the sink plant
- $qh_{i,kh}$ heat load between the intermediate fluid and hot stream i at stage kh in the source plant
- qcu_i heat load of the existing cooler for hot stream i in the source plant
- qhu_j heat load of the existing heater for cold stream j in the sink plant
- Din inside diameter of the pipeline
- $Dout$ outside diameter of the pipeline
- Wt weight per unit length (kg/m) of the pipeline
- $Pcul$ capital cost per unit length (\$/m) of the pipeline
- v viscosity of the intermediate fluid stream
- Re Reynolds of the intermediate fluid
- f fanning friction factor of the intermediate fluid
- ΔP pressure drop of the pump
- Qw pump power the intermediate fluid stream
- $Pipingcost$ annualized cost of pipeline
- $Pumpcapital$ capital cost of pump
- $Pumpoperation$ operation cost of pump
- $Pumpingcost$ the annualized cost of pump

Binary variables
- $zh_{i,kh}$ binary variables for contacts between intermediate fluid and stream i at stage kh
- $zc_{j,kc}$ binary variables for contacts between intermediate fluid and stream j at stage kc

Subscripts
- in inlet
- out outlet
- min minimum
- max maximum

Normally, hot water is selected as the intermediate fluid to recovery low grade heat between plants, which is also called as heat recovery loop (HRL). Kapil et al. [13] used HRL to extract waste heat from industrial plants and release it for district heating in the local energy systems. They emphasized the optimization should consider the distance factor, which had a significant importance on the integration performance. The integration results in their continuous work [14] showed plant-wide integration could reduce the overall energy consumptions on the site levels. Boldyryev and Varbanov [15] provided a consistent methodology to identify energy saving potential in low grade and hot water was used to accomplish the integration. They pointed out that the temperatures of the intermediate fluid were limited by the sink and source profile temperatures. Hackl et al. [16] studied energy collaboration between different plants using Total Site Heat Integration method. They suggested hot water as the intermediate fluid to build a more interconnected utility system for individual plants. A design methodology was developed by them to enable the collaboration flexible based on the energy efficient [17]. Atkins et al. [18] integrated HRL and the solar thermal system to improve energy