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A heat integration method with location-dependent heat distribution losses

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Abstract

Energy consumption in industrial processes is mainly in the form of heat. Thus, heat recovery is one of the main focuses in industrial energy efficiency problems. Heat integration (HI) techniques have been studied extensively to solve such problems. One of the main drawbacks of the classical heat integration approaches is that heat can be transferred from any stream to another as long as it flows from higher temperature intervals to lower ones, which results in impractical scenarios, in which heat is recovered over long distances. This work proposes a heat integration method which takes into account heat distribution losses. The heat losses are calculated as a function of the distance between the original location of the stream and the location it is used and the supply and return temperatures. The heat cascade is written so that the energy balance is closed for each location. This way, while heat recovery within the same or close location is promoted, heat transfer over long distances is discouraged. Using the proposed method, practically infeasible solutions are eliminated at the level of optimisation. At the same time, the temperature drop and the heat losses resulting from heat exchange over long distances are calculated. The method is applied to a case study with two plants. While the total operating cost can be reduced by 25% by heat integration within and between the sites, not exchanging heat between the two sites is found to be more beneficial when heat losses are taken into account.

Keywords: hear integration, heat distribution losses, multiple locations

1. Introduction

Energy efficiency has been a research-intensive field for more than forty years, initially motivated by fossil fuel prices and afterwards by environmental concerns. As one of the main energy consumers, the industrial sector, and more specifically process industry, has become the target of energy efficiency research. Energy consumption in industry is mainly in the form of heat. Hence, the research in the field focuses primarily on heat recovery and waste heat valorisation. Pinch analysis (PA) is a technique proposed by Linnhoff and Hindmarsh [1] which uses thermodynamics and a graphical representation of the streams to obtain the maximum energy recovery (MER) between the processes. Although PA has proven to be effective in setting targets for energy consumption, it can yield scenarios that are practically inefficient because of direct heat exchange between the processes. Dhole and Linnhoff [2] developed total site analysis (TSA), a method based on PA, to overcome this drawback. In TSA, heat is recovered from processes by means of utilities (e.g. steam, hot water, hot oil) and transferred to other processes that require heating. HI methods using mathematical programming (MP) have emerged to find the optimal utility configuration satisfying the MER. Typically, the problem is formulated with mixed integer linear programming (MILP), where the selection of the utilities is decided using binary variables and the size of each utility using continuous variables [3].

HI has been used for problems at different scales, including the optimization of a single process unit, a single plant and multiple plants. HI across industrial plants is typically achieved using intermediate fluids. Ahmad and Hui [4] used steam at different pressure levels to transfer heat between plants. Hackl et al. [5] proposed using a hot water loop to recover heat at low temperature in a chemical cluster. Rodera and Bagajewicz [6] studied both direct and indirect heat transfer across plants and concluded that more energy savings can be achieved by direct heat transfer and that steam is not always effective in indirect heat transfer.

Chew et al. [7] listed the layout of the plants as one of the crucial issues to be considered in heat integration. Several authors addressed this issue using different techniques. Wang et al [8] proposed a graphical method to consider interplant heat integration in parallel, split and series connection patterns and compared the energy savings and pipe length under different configurations. Song et al. [9] developed a graphical technique called interplant shifted composite curve to determine the maximum feasible heat recovery by indirect heat integration between plants. Chang et al. [10] proposed a mixed integer non-linear programming (MINLP) method to optimize waste heat integration between plants, including piping cost in the objective function. Stijepovic and Linke [11] presented a two-step optimization framework: in the first step, a linear programming (LP) problem is solved to obtain the maximum possible heat recovery; in the second step, a MINLP is used to achieve waste heat recovery with optimal design, accounting for piping cost.

A gap is identified when considering interplant heat integration since most of the existing methods do not consider the distance between plants in different locations. Some authors addressed the issue from an economic perspective, by including the cost of piping. However, the heat losses and the temperature drop due to the heat transfer over long distances have not been considered. This work focuses on heat losses resulting from interplant heat integration and proposes a MILP method based on [3] to obtain optimal heat integration scenarios for problems with multiple locations.

2. Methodology

2.1. Estimation of heat losses

The heat losses due to interplant heat transfer depend both on the pipe geometry and on the temperature of the heat transfer fluid. This work considers heat losses from pipes buried under ground as well as pipes above ground.

Heat losses from underground pipes

Heat distribution using pipes buried underground is common in urban district energy networks since it would be impossible to have the pipes above the surface in urban centres. This application is not very common in industry since urban planning rules do not apply to the industrial zones and installing pipes underground is costly. However, it is considered as an option in this work, since the ground provides insulation for the pipes, resulting in lower heat losses.

The formulas used in this work are adapted from the calculation of steady-state heat losses from buried pre-insulated district heating pipes (Bohm [12]) (Eqns. 1-5)

$$H = H' + \frac{\lambda_g}{h_{air}} \quad (1)$$

where H' represents the depth at which the pipes are buried, λ_g the thermal conductivity of the ground and h_{air} the convective heat transfer coefficient of air.

$$R_m = \frac{1}{4 \cdot \pi \cdot \lambda_g} \ln\left(1 + \left(\frac{2 \cdot H}{E}\right)^2\right), \quad R_g = \frac{1}{2 \cdot \pi \cdot \lambda_g} \ln\left(\frac{4 \cdot H}{D_i}\right), \quad R_i = \frac{1}{2 \cdot \pi \cdot \lambda_i} \ln\left(\frac{D_i}{D_p}\right) \quad (2)$$

where R_m, R_g, and R_i are the thermal resistance of the mutual action of the two pipes (i.e. supply and return), the ground and the insulation material, respectively. E is the distance between the pipes, λ_i is the thermal conductivity of the insulation material, and D_i and D_p are the diameter of the insulated pipe and of the pipe itself, respectively.

$$U_1 = \frac{R_g + R_i}{(R_g + R_i)^2 - R_m^2}, \quad U_2 = \frac{R_m}{(R_g + R_i)^2 - R_m^2} \quad (3)$$

$$\dot{Q}_{sup} = ((U_1 - U_2)(T_s - T_g) + U_2(T_s - T_r)) \cdot L_p \quad (4)$$

$$\dot{Q}_{ret} = ((U_1 - U_2)(T_r - T_g) - U_2(T_s - T_r)) \cdot L_p \quad (5)$$

where U_1 and U_2 are heat loss coefficients, L_p is the pipe length, T_s, T_r, and T_g are the temperatures of supply, return and ground, and $\dot{Q}_{sup}$ and $\dot{Q}_{ret}$ are the specific heat losses from supply and return.

<u>Heat losses from above surface pipes</u>

A simplified formulation is used to calculate the heat losses from above-ground pipes (Eq. 6-9). The temperature of the pipe is assumed to be equal to the temperature of the fluid flowing inside the pipe. This way, the convective heat transfer inside the pipe can be neglected.

$$\frac{1}{U} = \frac{1}{h_{air}} + \frac{t_p}{\lambda_p} + \frac{t_i}{\lambda_i} \quad (6)$$

$$A = 2 \cdot \pi \cdot D_i \cdot L_p \quad (7)$$

$$\dot{Q}_{sup} = U \cdot A \cdot (T_s - T_{amb}) \quad (8)$$

$$\dot{Q}_{ret} = U \cdot A \cdot (T_r - T_{amb}) \quad (9)$$

where t_p and t_i are the thickness of the pipe wall and of the insulation material, respectively, U is the overall heat transfer coefficient, A is the surface area of the insulated pipe and T_{amb} is the temperature of the ambient air.

Heat losses in the supply and return pipes are subtracted from the total heat load of the stream (Eq. 10).

$$\dot{Q}_s = \dot{Q}'_s - \dot{Q}_{sup} - \dot{Q}_{ret} \quad (10)$$

where $\dot{Q}'_s$ and $\dot{Q}_s$ are the heat loads of the stream prior to and after heat losses.

2.2. Modified MILP formulation

Maréchal and Kalitventzeff's MILP formulation [3] is modified to take into account the location of the streams and the heat losses. The set of locations ($\boldsymbol{L}$) is introduced and all units ($\boldsymbol{U}$) and streams ($\boldsymbol{S}$) are assigned to their corresponding locations by units of location

(**UL**) and streams of location (**SL**) sets. The streams that can exchange heat over distances are defined in a new set of interlocation streams ($\boldsymbol{IS} \in \boldsymbol{S}$) and added in **SL**. The temperature and heat load ($\dot{Q}_{s,t,k}$) of the interlocation streams are modified accounting for heat losses using Eq. 10. A stream can be split and used in several locations and to enforce the mass balance, a set of parents (**P**) and streams of parents in locations (**SP**) are defined to assign the usage of the same stream in different locations to the same parent.

The objective function (Eq. 11) is selected as the minimisation of the operating cost. The heat cascade equations (Eq. 12-14) ensure that heat flows from higher temperature intervals to lower ones. The objective function and the heat cascade are adapted from [3]. In the classical formulation, the heat cascade equations are written for each time step ($t \in \boldsymbol{T}$) and temperature interval ($k \in \boldsymbol{K}$). In the proposed formulation, they are also indexed over locations ($l \in \boldsymbol{L}$), to close the heat balance for each location.

$$\min_{y,f} \sum_{u=1}^{\boldsymbol{U}} \sum_{t=1}^{\boldsymbol{T}} (C_{u,t}^{op1} \cdot y_{u,t} + C_{u,t}^{op2} \cdot f_{u,t}) \cdot t^{op} \quad (11)$$

$$\sum_{u=1}^{\boldsymbol{U}} \sum_{s=1}^{\boldsymbol{SL}} \dot{Q}_{s,t,k} \cdot f_{s,t} + \dot{R}_{t,k+1,l} - \dot{R}_{t,k,l} = 0 \quad \forall\, t \in \boldsymbol{T},\ k \in \boldsymbol{K},\ l \in \boldsymbol{L} \quad (12)$$

$$\dot{R}_{t,k,l} \geq 0 \quad \forall\, t \in \boldsymbol{T},\ k \in \boldsymbol{K},\ l \in \boldsymbol{L} \quad (13)$$

$$\dot{R}_{t,1,l} = 0,\ \dot{R}_{t,k+1,l} = 0 \quad \forall\, t \in \boldsymbol{T},\ l \in \boldsymbol{L} \quad (14)$$

The contribution of this work is on determining the sizing factor of the streams ($f_{s,t}$). In the classical formulation, it is equal to the sizing factor of the unit ($f_{u,t}$) to which the streams belong. However, this must be modified as several streams are created to represent a stream in different locations. Eq. 15 is used instead, to set the sum of the sizing factor of a parent in different locations ($f_{p,l,t}$) to the sizing factor of the unit. Afterward, the stream sizing factors are fixed to the sizing factor of their parents (Eqn. 16).

$$\sum_{l=1}^{\boldsymbol{L}} f_{p,l,t} = f_{u,t} \quad \forall\, p \in P,\ u \in \boldsymbol{U}, t \in \boldsymbol{T} \quad (15)$$

$$f_{p,l,t} = f_{s,t} \quad \forall\, p \in P,\ l \in \boldsymbol{L}, s \in \boldsymbol{SP}, t \in \boldsymbol{T} \quad (16)$$

The descriptions of the parameters and variables used in the MILP formulation are given in Table 1.

Table 1. Description of the parameters and variables (bold) in the MILP formulation

Symbol	Description
$C_{u,t}^{op1}$	Fixed operating cost [€/h]
$C_{u,t}^{op2}$	Variable operating cost [€/h]
t^{op}	Operating time [h]
$\dot{Q}_{s,t,k}$	Heat from/to streams [kW]
$\boldsymbol{y_{u,t}}$	Binary variable to use a unit or not [-]
$\boldsymbol{f_{u,t}}$	Sizing factor of a unit [-]
$\boldsymbol{f_{p,l,t}}$	Sizing factor of a parent in a location [-]
$\boldsymbol{f_{s,t}}$	Sizing factor of a stream [-]
$\boldsymbol{\dot{R}_{t,k}}$	Residual heat in a temperature interval [-]

3. Case study and results

A case study with a single time step and two industrial plants that are 500 m apart from each other in both coordinates is considered (see Figure 1). Currently, both sites operate independently, using their own boilers and steam networks. However, the capacity of the boiler and of the steam network on Site2 can be extended in case the sites share their utility network.

Several scenarios are considered and compared with each other:

- Scenario 0 (s0): Both sites are operated at business as usual state. This scenario forms a basis for comparison with the energy saving solutions;
- Scenario 1 (s1): Heat integration is allowed within the boundaries of each site;
- Scenario 2 (s2): Heat integration is allowed within and between locations, without considering losses;
- Scenario 3 (s3): Heat integration is allowed within and between locations, considering losses for underground pipes. The steam network of Site2 is shared, Site1 does not have additional heating utilities;
- Scenario 4 (s4): Heat integration is allowed within and between locations, considering losses for the pipes above the ground. The steam network of Site2 is shared, Site1 does not have additional heating utilities.

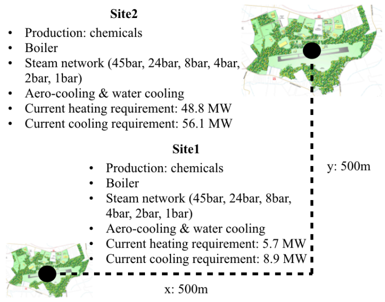

Figure 1. Case study layout

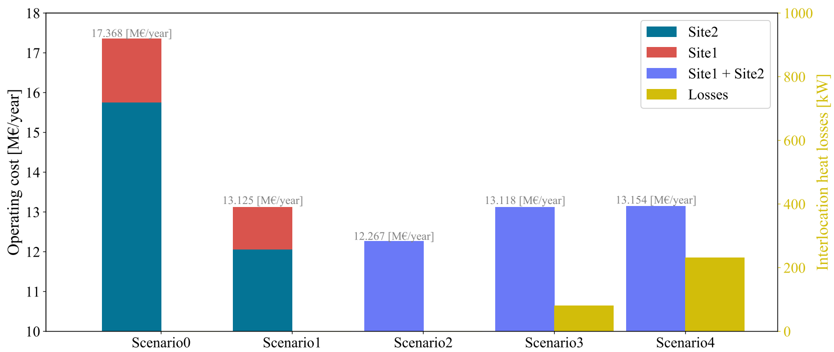

Figure 2. Operating cost and heat losses comparison of scenarios

The introduction of locations results in 10% increase in the number of variables, while a significant change in the solution time is not observed. The results of the case study are depicted in Figure 2. Comparing s0 and s1, when the two sites are optimised internally (i.e. without interplant heat transfer), the total operating cost reduces by 25% due to internal heat recovery on both sites and more efficient use of the steam network. In s2, the overall operating cost reduces by 30% compared to s0, due to heat recovery within and between sites. This scenario, representing the current state of the art in the literature, assumes no heat losses for interplant heat transfer. Hence, it sets the theoretical maximum heat recovery but it is likely to be impractical. In s3 the operating cost is 25% less compared to s0 and slightly less compared to s1. Thus, it is economically beneficial for the sites to use a common steam network with underground pipes. Heat is transferred using 1 bar and 2 bar steam between sites, which results in 82 kW of heat losses. In s4, the heat losses increase to 232 kW, since the pipes are considered to be above-ground. This scenario yields in an operating cost lower than the business as usual case, but slightly higher than s1. Therefore, it is better to optimise both sites internally, instead of using a common steam network.

4. Conclusions

In this work, a mathematical programming method is proposed to solve heat integration problems with several locations in which interplant heat exchange occurs. While the state of the art either neglects layout issues or considers them only from an economic point of view by accounting for piping cost, the proposed method gives additional insights by considering heat losses due to heat transfer over long distances. The method is applied to a case study with two sites in different locations. The total operating cost of the sites reduces by 30% applying the state of the art methods however the reduction becomes 25% when interplant heat losses are taken into account. While interplant heat transfer is still beneficial when heat distribution pipes are underground, it is not economically attractive when the piping is above the ground. In order to have a better economic analysis, the cost of piping should be included as a post calculation or in the objective function. This will be addressed in future work. The method can be used in heat integration studies to properly consider heat transfer over long distances and therefore obtain more realistic results.

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