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Cost Minimisation for Total Site Heat Recovery

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In this paper minimisation of total cost for retrofit of Total Site heat recovery system is proposed. It based on analysis of balanced Total Site Profiles and includes procedure for calculation of heat transfer area. Heat transfer area is calculated for different regions with use of intermediate utility and direct heating and cooling. Minimal temperature difference between Total Site Profiles is analysed. Global minimum of heat transfer area for Total Site recovery is calculated for array of minimal temperature differences. It is analysed with utility consumption, numbers of units and material of equipment. Selection of minimum total cost for retrofit project of site recovery system is proposed.

1. Introduction

Since EU leaders approved new energy policy the energy efficiency is becoming high priority for the next 15 y. On 23 October, EU leaders agreed on the 2030 climate and energy policy framework for the EU (EC, 2015). The European Council endorsed 4 targets:

- A binding EU target of at least 40 % less greenhouse gas emissions by 2030, compared to 1990;
- A binding target of at least 27 % of renewable energy used at EU level;
- An energy efficiency increase of at least 27 %;
- The completion of the internal energy market by reaching an electricity interconnection target of 15 % between member states and pushing forward important infrastructure projects.

The energy efficiency improvement is one of the key goals for future sustainable development. As reported by IEA in 2012 the industrial energy consumption is 28 % in overall world energy balance (see Figure 1). Energy saving potential in industry is still huge despite last time there are a lot of researches and applications which allowed reducing energy consumption considerably. They are mostly based on Pinch analysis, Mathematical Programming and Life Cycle Assessment as well as combinations and modifications of these methods as reported by Klemeš et al. (2014). For example Čuček et al. (2014) proposed the multi-period synthesis of an optimally integrated regional biomass and bioenergy supply network through a mixed-integer linear programing (MILP) approach. They obtained solutions with optimal selection of raw materials, technologies, intermediate and final product flows, and reduced greenhouse-gas emissions. Čuček et al. (2011) presented combination of mathematical programming and life cycle assessment for biomass and bioenergy supply chain. Boldyryev and Varbanov (2014) delivered the application of Pinch Analysis for bromine chemical plant and shown the reduction of energy consumption on 45 %.
Last time big progress was reached in energy efficiency improvement of individual industrial process and more attention should be paid to industrial sites. Firstly, it allows reducing energy consumption of industrial regions and decreasing pollution reduction considerably, secondly, it provides the possibility to utilise the industrial heat for residential and commercial sectors which are still big energy consumers. From the other hand it makes appropriate background to implement alternative energy sources including renewables that leads additional reduction of energy cost and improves environmental impact. These measures need well developed approaches which solve this type of system objectives. To utilise the waste industrial heat for different needs on site level the Total Site Analysis (TSA) should be used as was reported by Klemes et al.

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(1997). More recent developments shown that it could be based on different approaches. Karimkashi and Amidpour (2012) proposed a method for analysis an industrial energy system. It is based on the development and modifications of the R-curve concept which was previously developed by Kimura and Zhu (2000) and later updated by Varbanov et al. (2004). It was also used by Boldyryev et al. (2012) to estimate the investment for Total Site power cogeneration.

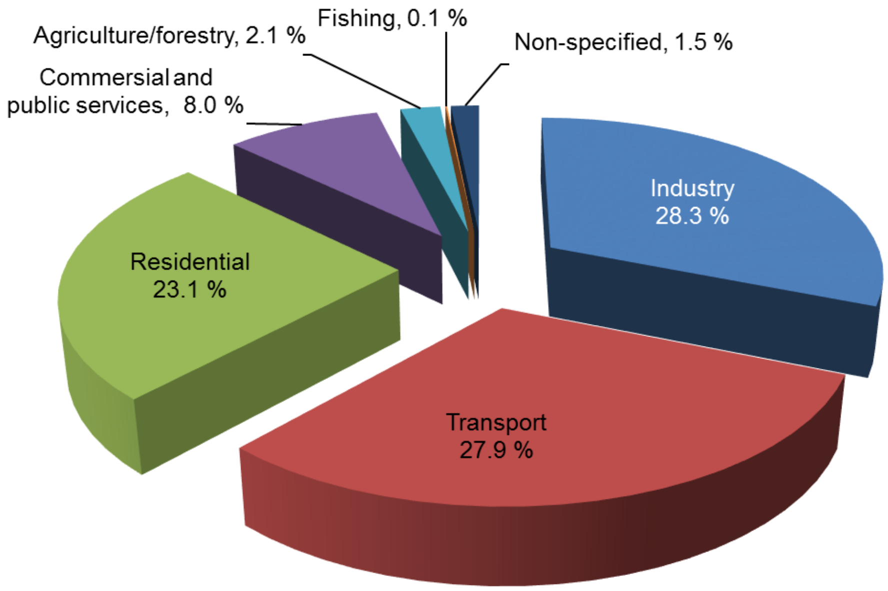

Figure 1: World energy balance 2012 (source IEA), 9 % of fuel is non-energy use.

Hackl et al. (2011) analysed large chemical site with use of the Total Site Analysis (TSA) method and proposed retrofit shown 50 % energy saving. But for low potential industrial heat utilisation the Total Site heat recovery could be used. Nemet et al. (2012) proposed the intermediate utility usage. This method was updated later by Boldyryev et al. (2014) and provided a methodology for minimisation of heat transfer area of Total Site heat recovery systems. Last time the authors were concentrated on development of methodology which allow minimise the heat transfer area of heat recovery on Total Site level. So, it was the significant step in estimation of retrofit targets of industrial site. This paper proposes the methodology to estimate minimum total cost for retrofit of Total Site heat recovery systems including energy and investments.

2. Methodology development

The authors previously proposed the procedure for estimating heat transfer area, which depends on a certain temperature levels of intermediate utility as reported by Boldyryev et al. (2014). It dealt with minimum heat transfer area for Total Site heat recovery. But there are other constituents of investments during retrofit such as numbers of heat exchangers as reported by Ahmad et al. (1990), specific temperature difference, utility targets, utility levels and prices which are influenced on total cost as shown by Kemp (2007). Methodology grounded on basic principles of Pinch Analysis (Klemeš et al., 2013) with some features of Total Site heat recovery. Last time a lot researches on Total Site heat recovery (Chew et al., 2015) investigate the possible heat integration without changing of temperature approach between Site profiles and do not take into account the costs for retrofit.

2.1 Procedure for total cost targeting

Procedure is consisted from following steps:

- Putting Total Site profile specifying minimum possible ΔT_{min} between profiles
- Determination of enthalpy intervals
- Selection optimum level of intermediate utilities
- Calculation of numbers of heat exchangers (boilers and condensers, heaters and coolers)
- Calculation of energy consumption

- Calculation of total cost
- Changing the ΔT_{min} between profiles and repetition of previous steps
- Selection of the Total Site ΔT_{min} with minimum total cost

Alternatives between big and small values of Total Site recovery are illustrated on Figure 2.

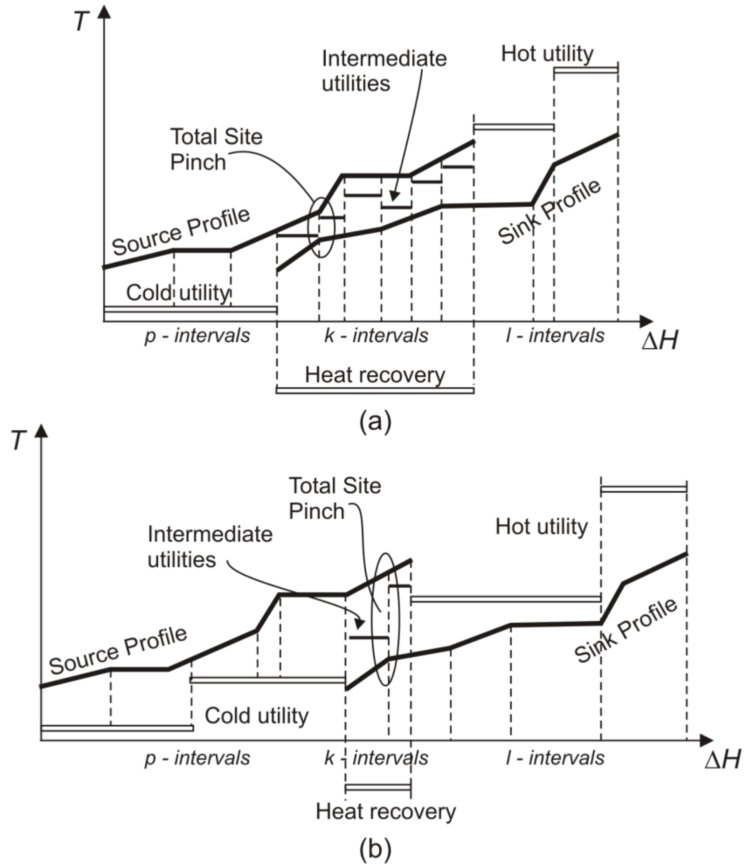

Figure 2: Total Site Profiles: a – expensive energy, big recovery; b – cheap energy, small recovery (developed after Dhole and Linnhoff, 1993)

2.2 Heat transfer area and number of heat exchangers

The heat transfer area is calculated for heat recovery regions, hot and cold utility regions Eq(1):

$$A_{Total} = A_{TSHR} + A_{TSHU} + A_{TSCU} \tag{1}$$

The heat transfer area for hot and cold utility regions is calculated as reported by Smith (2005) but for different levels of utility selecting the level of utility with minimal heat transfer area (Eq(2) and Eq(3)).

$$A_{TSHU} = \sum_{i=1}^{l} \min_{t1<t_{HU}<t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{HU}}{h_{HU}} \right)_i \tag{2}$$

$$A_{TSCU} = \sum_{j=1}^{p} \min_{t1<t_{CU}<t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{CU}}{h_{CU}} \right)_j \tag{3}$$

The equation for heat transfer area estimation presented by Boldyryev et al. (2014) should be modified minimizing heat transfer area of recovery system:

$$A_{TSHR} = \sum_{z=1}^{k} \min_{t1<t_{IM}<t2} \left(\frac{1}{\Delta T_{LM}^{H}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{IM}}{h_{IM}^{H}} \right) + \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{IM}}{h_{IM}^{C}} \right) \right)_z \quad (4)$$

The numbers of utility heat exchangers are calculated from basic principles of Pinch Analysis (Smith, 2005) assuming the number of heat exchangers are equal the number of streams in each enthalpy interval.

$$N_{HU} = \sum_{i=1}^{l} n_i^c, \qquad N_{CU} = \sum_{i=1}^{p} n_i^h \quad (5)$$

The number of heat exchangers for heat recovery is calculated for Sink and Source sides. There are dimensions of heat boilers and condensers for steam-condensate intermediate utility and heaters and coolers for hot water intermediate utility Eq(6). It is different from calculation of process-to-process heat exchangers because there are different intermediate utilities for recovery enthalpy intervals.

$$N_{HR} = \sum_{i=1}^{k} n_i^h + n_i^c \quad (6)$$

Total numbers of heat transfer equipment for Total Site heat recovery are calculated from Eq(7):

$$N_{Total} = N_{HR} + N_{HU} + N_{CU} \quad (7)$$

Figure 3 well illustrated the numbers of heat exchangers and definition of heat transfer area in enthalpy interval of Total Site Profiles.

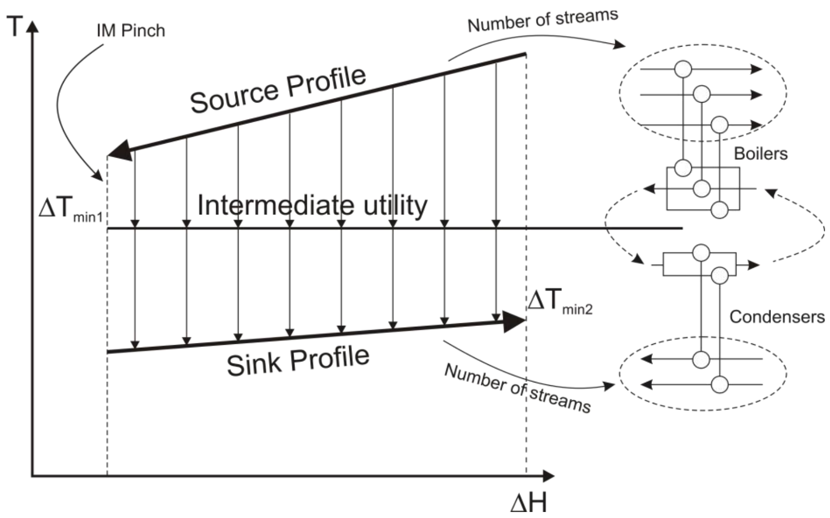

Figure 3: Streams and heat exchangers in enthalpy interval with intermediate utility (developed after Ahmad et al, 1990)

2.3 The energy consumption

For the last step it is needed to determine the utility demands, fuel and cooling media consumption. Hot and cold utilities demand for each Total Site ΔT_{min} are defined from Total Site Profiles (Klemeš et al, 1997) and shown on Figure 2. Total Site fuel consumption can be calculated from hot utility demands, ambient temperature, temperature of flue gases, coefficient of excess air and furnace efficiency. Cold utility consumption (e.g. cooling water, hot water, refrigerants etc.) can be determined from cold utility demands, temperature differences and efficiency.

The investment costs of Total Site heat recovery are calculated from minimum heat transfer area Eq(1), numbers of heat transfer equipment Eq(7) and equipment prices. The energy cost is defined from Total Site utility targets as said above and energy prices of different utilities.

3. Discussion

The paper is a step ahead to industrial application of the Total Heat Site heat methodology, it provides the decision making tool for the managers during retrofit and new projects. But there are some things are still needed deeper discussion and investigation.

The heat exchangers network for Total Site heat recovery is consisted of multiple steam boilers, condensers, water heaters and coolers. These equipment items are proposed to be placed for each enthalpy interval but it is still the possibility to simplification of heat exchangers network and finding the most profitable way between numbers of units and heat transfer area.

The number of heat exchangers and heat transfer area are increased comparison to individual process due to heat transfer via intermediate utility. From the other hand heat transfer coefficient for phase change is much higher than for heating and cooling of liquids and gases. In this case the heat transfer area has to be minimized as mentioned above and combined with numbers of units.

Calculating the total cost of heat recovery integration on Total Site the trade-off is determined. Energy costs have a big influence on it and using of different energy sources should be researched in future works. Low price energy sources move the retrofit project for low heat recovery to bigger energy consumption. It will decrease even realization of retrofit project which is so important for industrial site operation mode. This retrofit can be done during short time scheduled maintenance. To reduce this energy prices the renewables can be integrated into the Total Site but this should be well analysed from scheduling point of view and appropriate placement into the site supply side.

Additionally the combination of heat recovery with CHP should be analyzed for simultaneously application and calculation of investment and trade-offs. It can be done with use of mathematical programming and should be well targeted and grounded to get feasible solution.

4. Conclusions

The method allows to estimating minimum total cost for retrofit of site heat recovery systems. It makes a recommendation for selection of numbers of heat exchangers, numbers and levels of intermediate utility, hot and cold utility consumption on Total Site level. The results of this work may be used for further developments in Total Site methodology, for capital cost assessment with use of gas and steam turbines, renewables and specific process operations.

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Nomenclature

T – temperature, °C;
ΔH – enthalpy, MW;
A_{total} – total heat transfer area, m^2;
A_{TSHR} – minimum heat transfer area of heat recovery, m^2;
A_{TSHU} – minimum heat transfer area of hot utility, m^2;
A_{TSCU} – minimum heat transfer area of cold utility, m^2;
ΔT_{min} – minimal temperature difference between two process streams, °C
ΔT_{min1} – minimal temperature difference for source side, °C
ΔT_{min2} – minimal temperature difference for sink side, °C
ΔT_{LM}^{H} – logarithmic temperature difference for source side, °C
ΔT_{LM}^{C} – logarithmic temperature difference for sink side, °C
Q_i – heat of i hot stream, MW;
Q_j – heat of j cold stream, MW;
Q_{IM} – heat of intermediate utility in enthalpy interval, MW;
Q_{HU} – heat of hot utility in enthalpy interval, MW;
Q_{CU} – heat of cold utility in enthalpy interval, MW;
h_i – film heat transfer coefficient of i process stream, W/(m^2 °C);
h_j – film heat transfer coefficient of j process stream, W/(m^2 °C);
h_{IM}^{C} – film heat transfer coefficient for condensation of intermediate utility, W/(m^2 °C);

h_{IM}^{H} – film heat transfer coefficient for boiling of intermediate utility, W/(m^2 °C);
h_{HU} – film heat transfer coefficient of hot utility, W/(m^2 °C);
h_{CU} – film heat transfer coefficient of cold utility, W/(m^2 °C);
n – number of hot streams in enthalpy interval;
m – number of cold streams in enthalpy interval;
k – number of enthalpy intervals for heat recovery;
l – number of enthalpy intervals for hot utility;
p – number of enthalpy intervals for cold utility;
N_{HU} – number of heat exchangers for hot utility;
N_{CU} – number of heat exchangers for cold utility;
N_{HR} – number of heat exchangers for heat recovery;
N_{Total} – total number of heat exchangers;
n_i^h – number hot streams in enthalpy interval;
n_i^c – number hot streams in enthalpy interval;

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