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Heat Exchanger Network Modification for Waste Heat Utilisation under Varying Feed Conditions

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Waste heat streams are often neglected due to their comparatively low temperatures. However, they can still be utilised by retrofitting existing heat exchanger networks (HEN). Traditionally Pinch Analysis has been used to set heat recovery targets and these can be used as indicators for the retrofit. However, when an existing HEN contains a number of non-optimally placed heat exchangers, major topology modifications may be needed. As a result it may be more economic to achieve heat recovery smaller than the Pinch targets. In some cases exploiting or constructing utility-exchanger heat paths may be too costly and waste heat utilisation for added value side-product should be considered. In this paper the problems in retrofitting a HEN for utilities usage reduction are discussed. Additionally, HEN modification analysis is performed aiming at generating hot water as the value-added product. As the operating conditions vary, the modified network should also be flexible. These issues are addressed by a procedure development presented in this work, where different arrangements of HEN for modification are evaluated. The developed methodology is applied to a case study.

1. Introduction

Waste heat utilisation can provide additional degrees of freedom, when plant retrofit is performed. Waste heat loss is frequent in industry and especially in crude oil refineries. The low grade heat utilisation can increase the plant profitability by reducing the cold utility requirement or generating extra income from selling excess utility streams – e.g. steam or hot water. Sophisticated HEN designs based on Pinch Analysis are able to achieve thermodynamic targets of minimum utilities use (Klemeš, 2013). By appropriate HEN retrofit planning the utilities requirement can be reduced by increasing the heat exchange between hot and cold streams (Klemeš and Kravanja, 2013). Yong et al. (2014) provide an efficient visualisation tool for driving the modifications. In this analysis type, cold streams can be defined for representing preheating or drying operations. These streams have low temperature ranging from 50 °C to 150 °C. The retrofit can be done by re-sequencing or re-piping existing heat exchangers (Bakhtiari and Bedard, 2013), splitting streams (Pan et al., 2012), and by introducing new heat exchangers. It has also been found that the amount of heat exchanged can be increased by performing appropriate heat transfer enhancements guided by Pinch Analysis and Network Pinch identification (Pan et al., 2013). The advantage of the latter is that the topology of the HEN remains the same implying minimal investments. The Network Pinch retrofit approach depends on the availability of a heat path. When no heat path is available, it can be constructed by introducing a new heat exchanger between a hot and a cold stream that would connect coolers and heaters (Varbanov and Klemeš, 2000).

However, retrofitting an existing HEN to reduce utilities use is not always economically viable. This is especially true for HENs where such retrofits need many major topology modifications. They are also retrofit

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limitations for threshold problems – in this case hot or cold utility is not presented and no utility reduction can be achieved.

When retrofit for utilities usage reduction is deemed economically unfavourable for a network, the next level in hierarchy is to analyse waste heat utilisation options to produce value-added product. Waste heat can be e.g. used to dry biomass, when the plant is surrounded with supplies of wet biomass for energy production. Waste heat is also suitable to produce hot water as it can be generated with low temperature.

In this paper, an industrial case is evaluated, where waste heat from a small crude oil refinery plant is utilised to produce hot water for district heating purpose. The utilities use of the plant could be further reduced only by enrolling significant changes in the topology, therefore a modification of smaller scope has been evaluated. The refinery plant is also located in a climatic zone, where it is significant differences in ambient conditions during summer and winter. The crude oil feed to the refinery also varies. With different ambient temperatures across the seasons and different feed qualities, the HEN is modified in a way that waste heat can be used to produce hot water accounting for the parameter variations.

2. Methodology

In this section, different options for HEN retrofit under the described conditions are discussed. As an extension of the already developed retrofit methods, the current development focuses on the options for arranging heat exchangers in the HEN modifications. In the context of an oil refinery, hot water generation from waste heat can be considered as a cold utility. It is because its mass flowrate is not fixed by explicit specification and it provides an additional degree of freedom to the HEN under retrofit. Small waste heat loads may be sometimes not utilised if it is not economical. Other factors may also affect the decisions for splitting the process stream or the new utility stream. These include the cost for the piping, pipe and heat exchangers foundations and also some other important issues as e.g. the level of hazard of the process stream providing the waste heat (Chew et al., 2013). The water supply temperature can be lower if it is directly taken from a fresh source (e.g. river) or higher if water is returning from a hot water circuit. There are different ways of modifying the network for hot water generation from waste heat.

2.1 Parallel water heating with splitting the utility generation stream

The hot water generation stream can be split into branches matching the number of waste heat process streams. The distribution of the water CP for splitting depends on the amount of heat available and the final temperature of the water to be achieved after mixing. The advantage of a parallel arrangement is that the temperature differences in the new heat exchangers would be maximal as the hot water generation branches would always enter the heat exchangers at the water supply (starting) temperature. Therefore it would tend to require less heat transfer area than a series arrangement. Another advantage is that higher flexibility can be achieved accommodating the scenario variations.

The potential disadvantages of splitting include more complex piping, and more complex control. For instance, an added complexity in the simulation and optimisation for this arrangement is to ensure that the hot water target temperature specification is achieved without too much overshoot. There should be at least one branch that has a temperature higher than the target temperature for water specification. Potential other issues to prevent include evaporation and the danger of some branches not reaching the specified target temperature. As a result, it is important to specify the supply and target temperatures of the hot water to be produced, as this determines the waste heat streams suitable and the number of the hot water generation branches. Simulations and optimisations are necessary to identify the duties of the heat exchangers and the splitting ratios of the water stream. The final HEN should ensure that all the waste heat streams are considered, so that that each stream is utilised at least once in a scenario.

2.2 Series heating of the utility generation stream

In the second option the heat exchangers are arranged in series on the hot water generation stream. Choosing the right sequence of the heat exchangers is very important as the outlet temperature of one heat exchanger is the inlet temperature of another. This arrangement is easier to simulate and optimise as only the mass flowrate of the water stream and heating duties of heat exchangers are the variables. The disadvantage of this arrangement is that the modified network can be too specific for each scenario. Because of the single stream on the hot water generation sid, the flexibility of this topology would be lower. The supply and target temperatures of the hot water stream are important for this arrangement as well. The waste heat streams utilised should have temperatures high enough to be matched with the water stream. There are different ways to determine the order of waste heat streams to be heated, one of it is by ascending outlet temperature. This arrangement also needs simulation and optimisation to find the heat capacity flowrate and duties of the heat exchangers. To ensure that the final HEN is flexible, modifications should be done in a way permitting the feasible hot water generation in all scenarios. Different network modifications may be prompted by the various scenarios. One way to find the final network is to attempt adapting every modified network on every scenario. Any network topology found infeasible even in one scenario should be discarded. Should there be more than one feasible network, some criteria such as highest amount of hot water generation can be used to select final network.

2.3 Combination of parallel and series heating

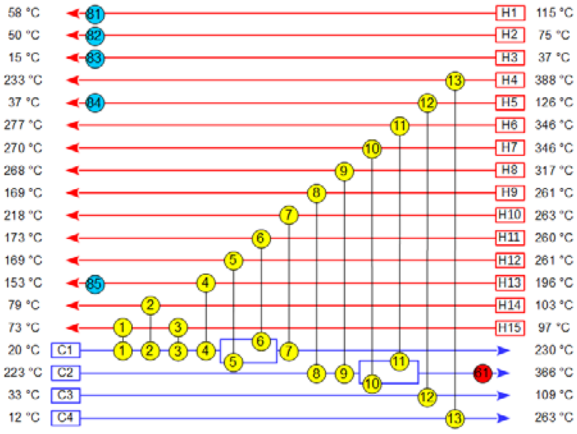
The HEN retrofit can also combine both parallel and series arrangements. Waste heat streams that have lower supply temperature are preferably cooled using in parallel arrangement. After the branches are heated up by the waste heat streams, they should then be mixed. Normally the temperature will be lower than the target hot water temperature specification. The merged stream can then be heated up with the higher temperature hot streams. The idea of having such an arrangement is to recover maximum amount of heat by having lowest possible temperature on the water side to receive heat from the lower temperature waste heat streams and highest possible heat capacity flowrate for high temperature waste heat stream. However, in this case the HEN is would be more complicated to modify to this arrangement as it needs more simulation and optimisation. Besides, the flexibility of this modification in different scenarios can also be questionable.

3. Case Study

A crude oil refinery is chosen to be the case study for this paper, applying atmospheric distillation. Due to the location of the refinery, it experiences summer and winter seasons and different feed condition of the crude oil results from the variation of the suppliers. Therefore there are total four scenarios labelled as A, B, C and D, with scenarios A and C occurring in the winter. Figure 1 shows the existing HEN in the plant with scenario A data.

The Pinch Analysis (Figure 2) on this unit shows that this is a threshold problem with no cold utility demand and hot water generation is not needed for maximum heat recovery. Further analysis has been performed and it shows that the minimum temperature difference in the current HEN is around 8 °C, which is a Network Pinch problem as the Pinch is not on the Pinch Temperatures (Asante and Zhu, 1997). The previous Pinch Analysis Targeting has been based on minimum temperature difference approach at 5 °C, identifying the Process Pinch. As the current HEN is not designed according to the Pinch Design Method (Klemeš, 2013), there is a larger use of hot utilities and high temperature hot streams exchange heat with low temperature cold streams, i.e. in the case of C1 exchanging heat with H14 and H15. This also results in excessive usage of cold utility compared with the thermodynamic target. All hot streams in the current HEN, that use cold utility, have low supply temperature (around 150 °C and below). Therefore they are considered as waste heat streams.

The two-level hierarchy has been applied in the analysis, with the first level of attempting to utilise waste heat for reduction of utility demands of the unit, while the second level attempts to utilise the waste heat for generating hot water as a side-product. The utility use reduction can be effected in an existing HEN by increasing the heat exchange between hot and cold streams. Finding paths that connect heaters to coolers or cooler-cooler / heater-heater via recovery heat exchangers was attempted for this purpose.



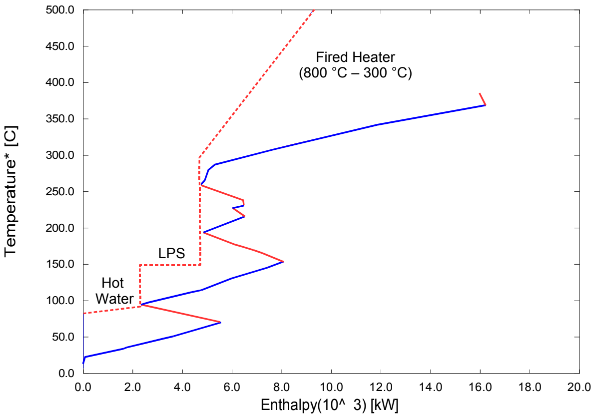


Figure 1: HEN of case study, data taken from Scenario A

Figure 2: GCC for Scenario A

Table 1: Waste heat streams qualified to produce hot water for scenario A

Stream	Supply Temperature (°C)	Target Temperature (°C)	Useful Target Temperature (°C)	Heat Capacity Flowrate (kW/K)	Useful Duty (kW)
H1	115	58	58	4.35	248
H2	75	50	55	34.2	684
H13	159	153	153	71.9	431

However, no such existing paths could be found. It is because that there are only four cold streams in the network. From them, three cold streams (C1, C3, C4 – Figure 1) are completely served by exchanging heat with hot streams, leaving only one cold stream that uses hot utility. Stream C2 is heated using furnace. No heat path exists that connects the furnace to a cooler. Constructing a heat path on this stream is impossible as its supply temperature for this stream is too high for the waste heat (hot) streams. To utilise the waste heat streams for utilities reduction, they can only be matched with the stream C1. This retrofit would require too many retrofit actions – such as re-sequencing, re-piping heat exchangers and splitting the cold stream. Attempting to construct new paths by adding new or moving the existing heat exchangers indicated that there would be needed more than two such modifications before a path would be established. Therefore reducing the use of utilities is possible but is likely to come at high investment cost.

Therefore the second level of the retrofit hierarchy is then attempted. In this paper parallel arrangement of the HEN is applied, i.e. the hot water generation stream is split and each waste heat stream is matched to a branch to exchange heat with the same low supply temperature of the water stream.

3.1 Modification steps on HEN for scenario A

The example HEN is modified according to steps described in section 2.1 for scenario A. According to the first step, the hot water generation stream is specified to have supply and target temperatures of 50 °C and 90 °C and minimum temperature difference approach between process and hot water is set at 5 °C. Therefore the waste heat streams to be used should be able to supply heat starting from 55 °C. Performing step 2 produces all the qualified waste heat streams from the network – see Table 1.

The third step is to split the water stream according to the number of the identified waste heat streams in Table 1. The water stream is then being split into three with three heat exchangers connecting them. Table 1 also shows that there is one having target temperatures less than 95 °C. Therefore at least one stream has to heat the water stream above 90 °C, so that when the branches are merged, the water stream should able to reach the desired target temperature. Care is taken so that the evaporation does not occur for the water stream, as doing so would induce higher equipment cost. Should there be no stream having target temperature higher than 95 °C, then there is no hot water generated and the modification process fails. Alternatively the insufficiently hot water would need to be passed via heaters spending fuel. The target temperature of the water stream should then be revised to have lower value. Step 4 connects each split stream and waste heat stream with heat exchangers.

Commercial software called Heat-INT (Process Integration Limited, 2014) is used to simulate and optimise the network for maximum hot water production. The heat exchanger duties and split ratio for the water system are obtained. Figure 2 shows the final optimised HEN modified for hot water production for scenario A. Table 2 shows the duties and split ratio for all three heat exchangers in scenario A.

Table 2: Specification for heat exchangers producing hot water for scenario A

Heat exchanger	Duty (kW)	Split ratio
14	413.7	0.628
15	5.5	0.008
16	240.0	0.364

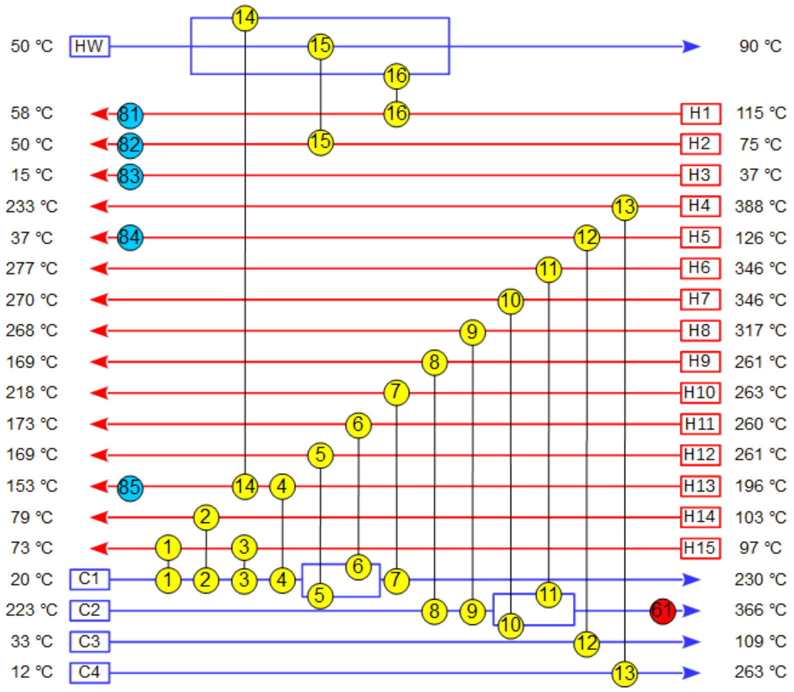


Figure 2: Modified HEN of the case study for scenario A

3.2 HEN for other scenarios

The steps are repeated, as mention in section 3.1, to produce the modified network for the other scenarios. A set of matches has been identified using the suggested methodology and tested in all scenarios. The final topology should contain all the streams in this list. In this case study, the list has all three streams that appear in every scenario. Therefore the final topology is the same as scenario A. Table 3 shows the simulated and optimised result.

4. Result and Discussion

In the analysis and modification, the modified topology of HENs in all four scenarios is the same. Only maximum three same waste heat streams are chosen to produce hot water in all four scenarios.

Table 3: Specifications for heat exchangers producing hot water for scenario B, C and D

Scenario	Heat exchanger	Duty (kW)	Split ratio
B	14	705.5	0.988
	15	6.55	0.009
	16	0.23	0.003
C	14	349.5	0.766
	15	15.33	0.034
	16	91.6	0.200
D	14	350.5	0.704
	15	2.34	0.020
	16	150.7	0.276

Table 4: Heat transfer area for all heat exchanger area in all the scenarios

Heat Exchanger	Scenario				Final Size
	A	B	C	D	
14	14.11	**19.27**	11.88	8.81	19.27
15	0.80	1.22	**2.70**	0.27	2.7
16	**62.02**	0.04	16.60	12.55	62.02

*All values are in m².

Therefore the final topology has three split streams and is compatible with each scenario. Table 4 shows the heat transfer areas for all heat exchangers in all the scenarios. The bolded values in Table 4 are the highest values for each heat exchanger. The heat exchangers should be then designed according to these values. However, specific request can be accommodated when designing the network. Although the network modifications are the same for all scenarios, the heat transfer area requirement is different for the same heat exchanger in different scenarios. It is desired to design the heat exchangers as small as possible to save the investment cost by considering different request. For example, if there is no hot water demand during the summer season and economic analysis shows that it is not profitable to produce it, the production of hot water can be stopped until is needed in winter. Then the heat exchangers can be designed according to the maximum values in scenarios A and C. During summer, the waste heat streams can be cooled by current existing coolers. Also an opportunity for the absorption cooling can be explored. Table 4 also shows some heat exchangers having very small final areas. For example heat exchanger 15, it is too small over all the scenarios. It should be singled out and recommended for further scrutiny.

5. Conclusion

This paper has successfully utilised waste heat under different feed conditions. Through a case study, it is determined that waste heat streams have too low temperature to reduce utilities consumption. Attempt to construct heat path for this purpose in this case study will lead to high investment cost. Therefore the HEN is then modified to generate hot water from the waste heat streams instead. The paper discusses different arrangements of heat exchanger and the effects of its flexibility and complexity under different conditions. The HEN in the case study is successfully modified using parallel arrangement. It uses three more heat exchangers with minimum production of 456 kW of hot water. All the heat transfer areas of heat exchangers are determined, which the highest values are used as the basis for design.

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