CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081086

Design and Operation Optimization of Industrial Waste Heat Recovery for District Heating and Cooling

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The recovery of industrial waste heat has drawn a lot of attentions, and integrating it into district heating and cooling (DHC) systems is a very attractive option for low-grade waste heat recovery. Most of the related studies used Pinch Technology to design the waste heat recovery networks for heating or refrigeration. However, district heating and cooling is a multi-period problem, and few of studies can provide specific operation plans in each different periods. In this study, a multi-period mathematical model has been established for the waste heat recovery, in which hot water is the intermediate fluid, and waste heat can be utilized in the entire year by integrating with DHC systems. The minimisation of total annual cost (*TAC*) of the system is regarded as the object function in the model. Operation parameters in each period including the mass flow rate and the temperature of hot water can be obtained by mathematical programming method. A case study has been conducted, and the optimal integration schemes were obtained by solving the mixed integer nonlinear programming (MINLP) model. The results show the significant potential economic benefits of the integration.

1. Introduction

Industrial waste heat is a kind of secondary energy, and it is the product of the utilisation of the primary energy in process industry. Generally, the high-grade and middle-grade waste heat can be easily recovered and utilized in the plant or inter-plant by Heat Integration (Klemeš et al., 2013). However, low-grade waste heat is difficult to be recovered and reused in the industrial field – both technically and economically – because of its low exergy. At present, low-grade waste heat is usually discharged into the environment by air or cooling water directly, which makes a large amount of energy wasted.

District heating and cooling (DHC) system is a system that delivers hot or cold water from a central energy station to buildings through large-scale underground pipe network. After three generations of development, the level of energy used in DHC system has become lower, which makes it much more feasible for low-grade industrial waste heat to be integrated into DHC system (Yu et al., 2017). By integrating low-grade industrial waste heat into DHC system, energy efficiency can be improved, fossil fuel combustion and greenhouse gas emissions can be reduced, and a large amount of cooling water can be saved. Kapil et al. (2011) proposed a method for identifying the quality and quantity of low-grade waste heat that can be recycled in the plant, and assessed the economic benefits of integrating waste heat into the district heating (DH) system. Kwak et al. (2012) applied the multi-period concept to the integration of low-grade waste heat with local energy system and obtained the optimal pattern of heat recovery and storage in a day. Fang et al. (2015) discussed three key issues faced by DH systems based on industrial waste heat, and designed the scheme of low-grade waste heat recovery for two plants in Chifeng, northern China.

As for the integration of low-grade waste heat and district cooling (DC) system, the technical issues have been discussed heavily. Absorption refrigeration can utilize low-grade waste heat to drive the operation of refrigeration cycle, it is an effective method to achieve the integration of low-grade waste heat and DC system (Lian et al., 2011). The widely used working medium of absorption refrigeration is LiBr-H_2O (Xia et al., 2018).

However, few of existing studies can give specific multi-period waste heat recovery schemes for the integration of low-grade waste heat and DHC system. Besides, most of the related studies used Pinch Technology to analyze the integration, the relevant operation parameters cannot be obtained directly. In view of the above

Paper Received: 30/03/2020; Revised: 24/04/2020; Accepted: 09/05/2020
Please cite this article as: Zhang L., Wang Y., Feng X., 2020, Design and Operation Optimization of Industrial Waste Heat Recovery for District Heating and Cooling, Chemical Engineering Transactions, 81, 511-516 DOI:10.3303/CET2081086

problems, the mathematical programming method is used in this study to design and optimise the multi-period heat exchange network (HEN) for waste heat recovery, by which the operation schemes in each season for the integration of low-grade waste heat and DHC system can be obtained simultaneously. The design and optimisation of multi-period HENs based on the mathematical programming has been researched by Verheyen et al. (2006), and their method has provided guidance for this work.

2. Problem statement

The work of this study can be summarized as establishing the multi-period Heat Integration between a plant and DHC system. The plant is the heat source, and there are several low-grade waste heat streams (also called ″hot streams″ in this paper) in the plant. Hot streams are cooled by the cooling water system in the plant when the waste heat is not integrated with DHC system, the coolers have been installed, so the capital cost of coolers are not considered in this paper.

In order to realise the Heat Integration, a small station needs to be built on the open space in the plant or near the plant, in which absorption refrigerator (LiBr-H_2O absorption refrigerator in this paper) and pumps are installed. There is a distance that cannot be ignored between the station and the production area where hot streams are located. Hot water is selected as the intermediate fluid, which is transported by the pump to the production area through pipelines, and then exchange heat with hot streams. After recovering the waste heat, the temperature of hot water rises and returns to the station. In winter, the hot water obtained can be directly sent to residential areas around the plant for district heating. In summer, hot water drives the operation of the absorption refrigerator in the station. After driving the refrigeration cycle, the temperature of hot water decreases, and the cold water produced can be sent to the buildings around the plant for district cooling. For some types of buildings, such as hospitals and data centers, cooling is also needed in spring and autumn, so the working mode of hot water in spring and autumn is the same as in summer, while the cooling capacity is less than in summer.

In order to obtain the scheme of waste heat recovery in each season, the stage-wise superstructure proposed by Yee et al. (1990) is employed to optimise the multi-period HEN. It should be noted that hot water cannot recover the whole low-grade waste heat generally due to the temperature demanded in DHC system, so cold utility is still needed in the plant. After establishing the integration, the cost of the entire system includes the capital cost of heat exchangers, the cost of cold utility, the capital cost of pump, the operation cost of pump, the capital cost of pipeline and the capital cost of refrigeration unit (including the cost of the staion's space), income can be obtained by selling hot and cold water. The main work of this study is to obtain the multi-period operation scheme for waste heat recovery to minimizes the total annual cost (*TAC*) of the entire system, so the objective function is Eq(1).

$$\min\left\{TAC = C_{cu} + C_{exchanger} + \mathrm{C}_{refrigerator} + C_{pipe} + C_{pump,cap} + C_{pump,op} - Inc\right\} \tag{1}$$

3. Mathematical formulation

There are two sets need to be declared. Hot streams are defined by index *i*, $i \in I$, the index sets are I = {*H1*, *H2*, …, *Hn*}. Periods are defined by index *s*, $s \in S$, the index sets are S = {*spring*, *summer*, *autumn*, *winter*}.

3.1 Model of HEN

The stage-wise superstructure is employed to describe the HEN for waste heat recovery. The detailed basic formulation can be found in the work of Yee et al. (1990). Some additional constraints are added in this model. In the current DH system, the temperature of atmospheric hot water delivered to residential areas is generally required to be not lower than 80 °C. In this paper, the temperature of water returning back to the station is fixed to be 40 °C, so the boundary constrains of inlet and outlet temperatures of hot water in winter are shown in Eq(2) and Eq(3).

$$80 \le Twout_s \le 100 \quad s = winter \tag{2}$$

$$Twin_s = 40 \quad s = winter \tag{3}$$

The coefficient of performance (*COP*) of the absorption refrigerator is related to the temperature of the driving heat. Wang et al. (2017) studied the relation between the *COP* of single-effect LiBr-H_2O refrigerator and the temperature of hot water that drives the refrigeration cycle. On their research conditions, when the temperature of cold water is determined, there is a significant linear relation between the temperature of hot water entering and leaving the refrigerator. Eq(4) can be obtaioned by linear fitting, in which $Twout_s$ ranges from 100 to 150 °C.

$$Twin_s = 0.426 \cdot Twout_s + 52.8 \quad s = spring, summer, autumn \tag{4}$$

The heat transfer area needed for hot water to recover the heat of hot stream *i* at stage *k* in period *s* is calculated by Eq(5), in which the variable $LMTD_{i,k,s}$ is the logarithmic mean temperature difference. In order to reduce the difficulty of the solution, Chen approximation (Chen, 2011) is used for the calculation of $LMTD_{i,k,s}$, which is shown by Eq(6). For multi-period HEN, the design area of a heat exchanger should be the maximum area that needed in all periods (Verheyen et al., 2006), this relationship is expressed in Eq(7).

$$Aes_{i,k,s} = q_{i,k,s} \cdot (hw^{-1} + hh_i^{-1}) / LMTD_{i,k,s} \tag{5}$$

$$LMTD_{i,k,s} = \left[dt_{i,k,s} \cdot dt_{i,k+1,s} \cdot (dt_{i,k,s} + dt_{i,k+1,s}) / 2 \right]^{1/3} \tag{6}$$

$$Ae_{i,k} \geq Aes_{i,k,s} \tag{7}$$

The capital cost of heat exchangers and the cost of cold utility are calculated by Eq(8) and Eq(9).

$$C_{exchanger} = Af \cdot \left[\alpha \cdot \sum_{i \in I} \sum_{k \in st} z_{i,k} + \beta \cdot \sum_{i \in I} \sum_{k \in st} Ae_{i,k} \right]^{\gamma} \tag{8}$$

$$C_{cu} = \sum_{i \in I} \sum_{s \in S} upcu \cdot \frac{t_s}{t_{total}} \cdot qcu_{i,s} \tag{9}$$

3.2 Model of absorption cooling machine

As mentioned, hot water is used for refrigeration in spring, summer and autumn, so the element *s* = *winter* is not involved in this section. The cooling capacity of the single-effect LiBr-H_2O refrigerator can be calculated by Eq(10) when the consumption of electricity can be ignored (Wang et al., 2017). The values of refrigerator's *COP* at different hot water temperatures (that is $Twout_s$ in this paper) were provided by Wang et al. (2017). In order to describe the mathematical function for these two variables, the piecewise linearization is employed, the result is expressed in Eq(11).

$$Qcs_s = COP_s \cdot \left[cpw \cdot mw_s \cdot (Twout_s - Twin_s) \right] \quad s = spring, summer, autumn \tag{10}$$

$$COP_s = \begin{cases} 0.0437 \cdot Twout_s - 4.217 & (100 \leq Twout_s \leq 110) \\ 0.0082 \cdot Twout_s - 0.312 & (110 \leq Twout_s \leq 120) \\ 0.0043 \cdot Twout_s - 0.156 & (120 \leq Twout_s \leq 130) \\ 0.0018 \cdot Twout_s - 0.488 & (130 \leq Twout_s \leq 150) \end{cases} \tag{11}$$

In this study, the cooling capacity in spring and autumn is set to be equal, and the cooling capacity in spring and autumn is smaller than that in summer. The relationship is shown in Eq(12), in which ε is set to 0.5.

$$Qcs_{spring} = Qcs_{autumn} = \varepsilon \cdot Qcs_{summer} \tag{12}$$

The capital cost of the refrigeration unit is calculated by Eq(13).

$$C_{refrigerator} = Af \cdot \left(a + b \cdot Qc_{summer} \right) \tag{13}$$

3.3 Model of pipe

The intermediate fluid (hot water) is circulated between the station and the production area via pipelines. The atmospheric water is used in winter, while pressurised water is used in spring, summer and autumn. Schedule 40 steel pipes are used in winter, while schedule 80 steel pipes are used in other seasons. Because of the significant difference between the cooling capacity in spring / autumn and summer, the mass flow rate of hot water is also quite different. In order to ensure that hot water flows at an appropriate velocity in each period, hot water in spring and autumn shares the same pipeline,while hot water in summer uses another pipeline. There are three supply and return pipelines for hot water between the plant and the production area.

The inner diameter of pipeline is calculated by the method of Peters et al. (2002), and the capital cost of pipeline per unit length $Pcul_s$ is calculated by the method of Stijepovic et al. (2011). Based on their methods, the total capital cost of pipelines in this paper is calculated by Eq(14).

$$C_{pipe} = Af \cdot 2 \cdot L \cdot \left(Pcul_{spring} + Pcul_{summer} + Pcul_{winter} \right) \quad (14)$$

3.4 Model of pump

The pump is used to overcome the pressure drop of hot water. In Eq(15), the total pressure drop of hot water includes two parts: the pressure drop because of the distance between the station and the production area, and the tube side pressure drop in heat exchangers.

$$\Delta p_s^{total} = \Delta p_s^{distance} + \Delta p_s^{exchanger} \quad (15)$$

The variable $\Delta p_s^{distance}$ is calculated by the method of Chang et al. (2016). The calculation method of pressure drop of hot water in heat exchangers of can be found in the work of Soltani et al. (2011). If fluid flows in parallel, the pressure drops of all branched are equal in a stable condition. In the stage-wise superstructure, the pressure drop of hot water at each stage is equal to the maximum pressure drop in heat exchangers at this stage, this relationship is expressed in Eq(16). The total pressure drop of hot water in heat exchangers is calculated by Eq(17). The power of pump in each period is calculated by Eq(18), and the rated power of pump is expressed in Eq(19).

$$\Delta p_{k,s}^{stage} \geq \Delta p_{i,k,s}^{tube} \quad (16)$$

$$\Delta p_s^{exchanger} = \sum_{k \in st} \Delta p_{k,s}^{stage} \quad (17)$$

$$Power_s = \frac{mw_s \cdot \Delta p_s^{total}}{\rho_s} \quad (18)$$

$$Prate \geq Power_s \quad (19)$$

The capital cost and operation cost of pump are calculated by Eq(20) and Eq(21).

$$C_{pump,cap} = Af \cdot \left(c_1 + c_2 \cdot Prate^{c_3} \right) \quad (20)$$

$$C_{pump,op} = upe \cdot \sum_{s \in S} \frac{Power_s \cdot t_s}{1000 \cdot \eta} \quad (21)$$

3.5 Calculation of income

The total income is calculated by Eq(22).

$$Inc = upc \cdot \left(Qcs_{spring} \cdot t_{spring} + Qcs_{summer} \cdot t_{summer} + Qcs_{autumn} \cdot t_{autumn} \right) + uph \cdot \sum_{i \in I} \sum_{k \in st} q_{i,k,winter} \cdot t_{winter} \quad (22)$$

4. Case study

4.1 Data

The hot streams data in this case is shown in Table 1. There are two sets of physical parameters for hot water. The density and viscosity of atmospheric water in winter are 980 kg/m^3 and 0.430 mPa·s, and the density and viscosity of pressurised water in other seasons are 945 kg/m^3 and 0.242 mPa·s. The distance between the station and the production area *L* is 400 m in this case.

Table 1: Data of hot streams

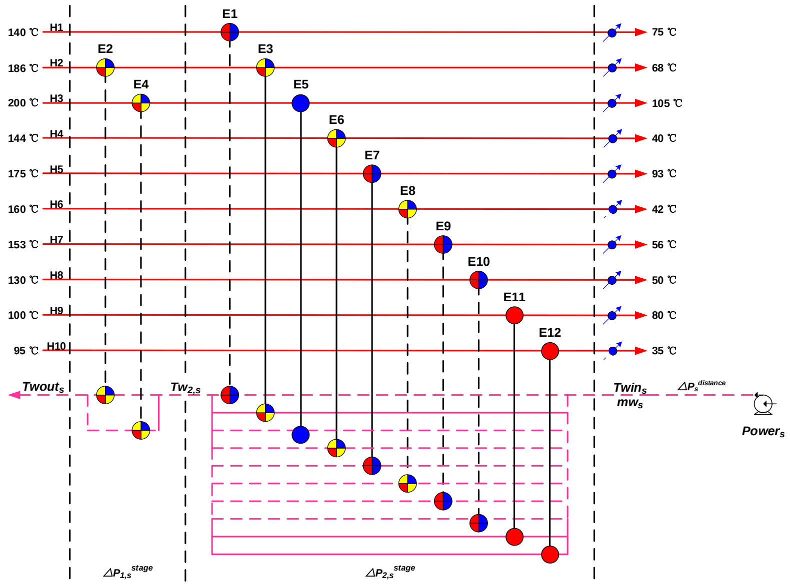
i	*Thin$_i$* (°C)	*Thout$_i$* (°C)	*Fh$_i$* (kW/°C)	*i*	*Thin$_i$* (°C)	*Thout$_i$* (°C)	*Fh$_i$* (kW/°C)
H1	140	75	24	*H6*	160	42	40
H2	186	68	34	*H7*	153	56	32
H3	200	105	38	*H8*	130	50	35
H4	144	40	30	*H9*	100	80	54
H5	175	93	30	*H10*	95	35	26

Table 2: Economic parameters of case study

Items	Data	Items	Data	Items	Data	Items	Data
Af	0.264	*a*	400,000 $	c_2	7310 $/W$^{0.2}$	*upe*	0.1 $/kW·h
α	11,000 $	*b*	400 $/kW	c_3	0.2	*upc*	60 $/MW·h
β	150 $/m^2	c_1	8600 $	*upcu*	15 $/kW·y	*uph*	100 $/MW·h
γ	1.0						

4.2 Results

In this paper, the program of the MINLP model was coded in the software GAMS, the solver DICOPT was used. The multi-period HEN for waste heat recovery was obtained, which is shown in Figure 1. There are 12 heat exchangers in the HEN, 5 heat exchangers（yellow）operate in spring and autumn, 10 heat exchangers (blue) operate in summer, and 11 heat exchangers (red) operate in winter. Economic data is shown in Table 3.



Exchangers	*Ae* (m^2)	$q_{spring/autumn}$ (kW)	q_{summer} (kW)	q_{winter} (kW)
E1	57.7	0	604.8	1560.0
E2	78.5	1303.7	1803.7	2732.8
E3	71.9	659.8	617.1	1279.2
E4	96.1	1966.0	2528.5	3610.0
E5	81.2	0	709.1	0
E6	145.7	475.3	876.0	2820.0
E7	98.9	0	1806.0	2460.0
E8	196.4	1332.0	1808.0	4400.0
E9	124.2	0	1222.4	3104.0
E10	169.4	0	532.0	2800.0
E11	56.4	0	0	1080.0
E12	143.4	0	0	1170.0

s	*spring / autumn*	*summer*	*winter*
mw_s (kg/s)	41.0	163.6	122.4
$Twin_s$ (°C)	116.7	104.8	40.0
$Tw_{2,s}$ (°C)	131.0	116.7	80.2
$Twout_s$ (°C)	150.0	123.0	92.5
$Power_s$ (kW)	1.711	4.184	5.796
$\Delta p_s^{distance}$ (Pa)	28780	17489	22210
$\Delta p_{1,s}^{stage}$ (Pa)	4171	1011	1627
$\Delta p_{2,s}^{stage}$ (Pa)	6466	5663	22562
Qr_s (kW)	5737	12508	27016
Qhs_s (kW)	0	0	27016
Qr_s (kW)	4303	8605	0
COP_S	0.750	0.688	0

Figure 1: The multi-period operation scheme

Table 3: Economic data of the results

TAC ($)	C_{cu} ($)	$C_{exchanger}$ ($)	$C_{refrigeratorr}$ ($)	C_{pipe} ($)	$C_{pump,cap}$ ($)	$C_{pump,\ op}$ ($)	*Inc* ($)
-6,839,225	194,088	87,046	1,032,011	215,453	13,178	4,810	8,385,811

4.3 Discussion

It can be seen from Table 3 that the *TAC* is much lower than zero, which indicates that the design can make profit. If the waste heat is not recovered, it can be calculated that the cost of cold utility is 4.204 × 10^5 $/y, which means that the cooling duty of cold utility is also reduced, and indicates that the potential benefit of the integration in this case is up to 7.260 × 10^6 $/y.

The outlet temperature of hot water $Twout_s$ in HEN is an important decision variable in all periods. In winter, when the total heat load recovered is constant, the higher temperature of hot water leads to the lower temperature approaches of heat exchangers, and the larger total heat exchange area is needed. The mass flow rate of hot water will decrease because of the rise of temperature difference, leading to the lower cost of pipeline and pump. In other seasons, besides the above effects, the variable $Twout_s$ can make a difference to the COP_s of the refrigerator. It can be seen from Eq(11) that with the rise of $Twout_s$, the variable COP_s increases rapidly at the beginning, and then increases slowly. At the same time, the corresponding $Twin_s$ rises too, which means the less waste heat that can be recovered. When the $Twout_s$ is too low, the quantity of waste heat recovered is relatively large, but the efficiency of refrigeration is too low; Contrarily, when the $Twout_s$ is too high, the quantity of waste heat recovered decreases, but the COP_s increases not significantly. In summer, when the $Twout_s$ is too low or too high, the optimal cooling capacity of the refrigerator cannot be reached. However, the cooling capacity is relatively small in spring and autumn. The rise of $Twout_s$ can reduce the cost of pipeline and pump, so the outlet temperature of hot water in spring and autumn is 150 °C (the maximum value limited in this paper).

Because of the large temperature range of hot streams, only one temperature stage is not enough, so the result that the HEN has two stages is reasonable. The inlet temperatures of *H2* and *H3* are relatively high, so there are heat exchangers at both stages. In summer, the heat exchangers E11 and E12 are shut down due to the low temperature levels of *H9* and *H10*, which are not high enough to heat the pressurised hot water. In winter, because the area of E5 is not large enough to heat the hot water to the middle temperature (82.5 °C), E5 is shut down and the heat of *H3* is recovered by E4 entirely.
The limitation of this paper is that only the optimisation of Heat Integration within the heating/cooling side (the plant) is considered, and the combination with objects with heating/cooling demand is ignored. The future development is to incorporate the match and selectivity of heating/cooling into the model.

5. Conclusions

In this paper, a multi-period optimisation model for the integration of industrial low-grade waste heat and DHC system has been established, in which waste heat is utilised for heating in winter and for cooling in other seasons. By solving the MINLP model, the optimal operation scheme for waste heat recovery in each season can be obtained, including the number of operating heat exchangers, the mass flow rate and outlet temperature of hot water, and the power of pump, etc. A case study has been conducted and the results showed that potential benefit of the integration is more than 7 M$/y. Among the operation parameters, the outlet temperature of the intermediate fluid (hot water) in HEN is an important optimisation variable, which leads to the trade-off between the several costs. The optimal results indicate that the temperature of hot water obtained for heating in winter is 92.5 °C, the temperature of hot water for refrigeration should be 123 °C in summer and 150 °C in spring / autumn. The results also provide the integration potential between waste heat and DHC system at the same time. The heating potential is 27,000 kW and the cooling potential is 8,600 kW in this paper.

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