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Discovering the Potential of Absorption Refrigeration System through Industrial Symbiotic Waste Heat Recovery Network

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Waste heat recovery technology (WHRT) is gaining much attention from both researchers and industrial players as it can reduce the electricity usage and the environmental impact. Waste heat released in the form of low grade heat such as steam, flue gas and hot water can be utilized to drive an absorption refrigeration system (ARS) for chilled water production. In previous work, chilled and cooling water network (CCWN) was synthesized within an eco-industrial park (EIP) to enhance energy conservation. However, the integrated CCWN from the previous work was configured using vapor compression refrigeration system (VCRS), a conventional method that uses electricity to generate chilled water. The main aim in this work is to extend previous work by integrating CCWN in centralized VCRS and ARS utilizing various types of waste heat that exist in a total site. A case study was presented to study the economic performance and sustainability of cooling resources by recovering different waste heat in an integrated EIP. The main contribution in this paper is to propose an integrated energy system to simultaneously reduce industrial waste emission and the overall energy consumption of the CCWN.

1. Introduction

Globalization of the economy, coupled with the growth of world population, has led to the increasing energy demand. To decouple the economic growth from environmental pressure, the concept of interplant resource sharing and total site process integration have been widely studied. Zhang et al. (2016) proposed a waste heat recovery network (WHRN) within an eco-industrial park (EIP) to improve the overall energy efficiency by promoting the interplant transportation of hot stream. Hassiba et al. (2017) developed an approach to utilize different grades of waste steam generated from an EIP for electricity and hot water generation through co-generation technology. Boldyryev et al. (2014) proposed a methodolgy to reduce the capital cost for the design of heat exchanger network (HEN) on a total site level.

Chilled and cooling water are the two common utilities used in most of the industries. Conventional chilled water system is driven by vapour compression refrigeration system (VCRS), which require high electricity consumption. In comparison to VCRS, absorption refrigeration system (ARS) could utilize waste heat (eg. steam, flue gas, hot water) from industrial plants to produce chilled water. In an ARS, the working fluid is a binary solution consisting of refrigerant and absorbent. Generally, the industrial waste heat source evaporates the refrigerant in the generator while the cooling duty is generated from evaporator through removing the excess heat from the refrigerated space. Many studies have been carried out to investigate the performance of ARS and VCRS in energy and economic aspects. Liew et al. (2016) performed total site heat integration for district cooling system using electricity and low-pressure steam from co-generation system to drive the VCRS and ARS. Kwak et al. (2014) performed economic analysis on various waste heat recovery technologies and found that ARS is less profitable compared to other waste heat recovery refrigeration system. The comparison between the ARS and VCRS was not addressed in the work of Kwak et al. (2014).

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The previous work by Leong et al. (2015) demonstrated the synthesis of an integrated chilled and cooling water network (CCWN) with centralized VCRS in an EIP to improve both savings in energy and operating cost. There is a research gap that remains to fully realize the potential of ARS in a total site specifically on the integration of WHRN utilizing various types of waste heat available in each plant to synthesize an energy efficient CCWN. Hence, this paper proposed a sustainable waste heat management and utilization using process integration and optimization approach, reducing the electricity consumption for producing chilled water which is an important utility in any industry. Three different types of waste heats, waste hot water (WHW), waste steam (WHS), and waste flue gas (WFG), are integrated into a centralized ARS and VCRS. An optimal WHRN will be developed to minimize the fresh energy consumption by partial or total elimination of VCRS.

2. Problem Statements

Given is a set of industrial plants p ∈ P, each of which is planning to participate in an EIP by recovering their waste heat in ARS for chilled water production. Each participating plant has its own predefined temperatures and flowrates for chilled and cooling water input requirement (sinks j ∈ J) and returned chilled and cooling water sources i ∈ I for reuse/recycle in CCWN. The existing waste heat sources to be recovered within the total site are predefined with temperature and specific heat capacity.

3. Methodology

The proposed superstructure in this paper consists of a centralized chilled water generation hub integrated with VCRS and ARS. The objective of this work is to synthesis an optimum network by minimizing the overall total annual cost (TAC), which consists of investment cost of ARS, VCRS and cooling tower (CT) and inter-plant piping cost. The objective function for the base case is Eq(1) and the case study is Eq(2):

$$min\,TAC = CAPCT + CAPVCR + CAPPC + OPC \tag{1}$$

$$min\,TAC = CAPCT + CAPVCR + CAPARS + CAPPC + OPC \tag{2}$$

where $CAPCT, CAPVCR, CAPARS$ and $CAPPC$ denote the capital costs of CT, VCRS, ARS, and interplant piping. OPC is the operating cost for CCWN (i.e. electricity, makeup water) and ARS waste heat cost (i.e. WFG treatment cost, WHW and WHS purchase cost).

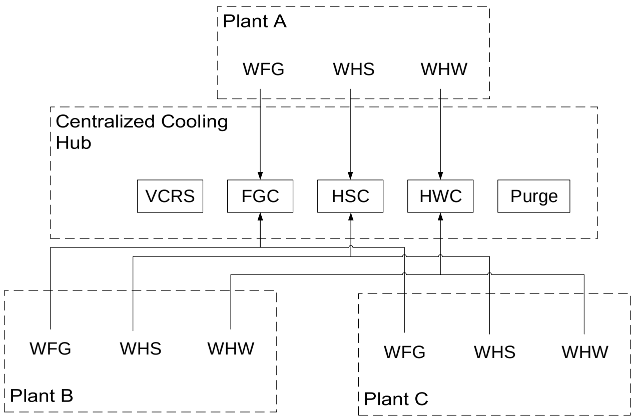

Figure 1: Waste heat and refrigeration system superstructure representation for proposed network (HSC = Hot steam ARS, HWC = Hot water ARS, FGC = Flue gas ARS)

The base case shown in in this paper is adopted from the previous literature by Leong et al. (2016). The superstructure involves a centralized VCRS integrated within an EIP without considering waste heat recovery. To extend the work in Leong et al. (2016), an integrated WHRN is proposed in the centralized cooling hub, as shown in Figure 1. Note that for generic purpose, three types of ARS (HWC, HSC and FGC) were placed in the centralized utility hub for WHW, WHS and WFG (Figure 1).

Noted that the detailed modelling equations for the CT and the VCRS model can be found from Leong et al. (2016). The following section shows the modelling equations for ARS. The inlet stream of the centralized ARS is defined as the sum of the returned streams from source i and the outlet stream of the centralized ARS is the sum of the regenerated chilled water from centralized ARS. The ARS chilled water mass and energy balance are given as follow:

$$\sum_{p \in P} \sum_{i \in I} F_{ri,ars,p} = F_{in,ars} \qquad \forall i \in I_p,\ \forall p \in P \tag{3}$$

$$F_{out,ars} = \sum_{p \in P} \sum_{j \in J} F_{ars,j} \qquad \forall i \in I_p,\ \forall p \in P \tag{4}$$

$$\sum_{p \in P} \sum_{i \in I} F_{ri,ars,p}\, T_{out,ars} = F_{in,ars} T_{in,ars} \qquad \forall i \in I_p,\ \forall p \in P \tag{5}$$

where $F_{ri,ars,p}$ is the return chilled water flowrate from each plant, $F_{in,ars}$ is the ARS chilled water inlet flowrate, $F_{out,ars}$ is the ARS chilled water outlet flowrate, $F_{ars,j}$ is the supply chilled water flowrate to plant, $T_{in,ars}$ is the ARS chilled water return temperature and $T_{out,ars}$ is the ARS chilled water supply temperature.
The energy supplied by the waste heat sources for the ARSs is described as follows:

$$WH_{ars01} = F_{wfg,ars01}\, C_{p,wfg}\, (T_{wfg,in01} - T_{wfg,out01}) \tag{6}$$

$$WH_{ars02} = F_{whs,ars02}\, \lambda_{whs} \tag{7}$$

$$WH_{ars03} = F_{whw,ars03}\, C_{p,whw}\, (T_{whw,in03} - T_{whw,out03}) \tag{8}$$

where WH_{ars01} is the waste heat supplied by WFG, WH_{ars02} is the waste heat supplied by WHS, WH_{ars03} is the waste heat supplied by WHW, $C_{p,wfg}$ is the specific heat capacity of WFG , λ_{whs} is the latent heat of WHS, $C_{p,whw}$ is the specific heat capacity of WHW, $T_{wfg,in01}$ is the WFG inlet temperature, $T_{wfg,out01}$ is the WFG outlet temperature, $T_{whw,in03}$ is the WHW inlet temperature, $T_{whw,out03}$ is the WHW outlet temperature, $F_{wfg,ars01}$ is the WFG source flowrate, $F_{whs,ars02}$ is the WHS source flowrate and $F_{whw,ars03}$ is the WHW source flowrate.
The overall energy balance for ARS is described as follow:

$$Q_{abs-con,ars} = PC_{pump,ars} + WH_{ars} + Q_{evap,ars} \tag{9}$$

$$Q_{abs-con,ars} = F_{cw,ars} c_{p,water} (T_{cwo,ars} - T_{cwi,ars}) \tag{10}$$

$$\sum_{01,02,03} WH_{ars} = \sum_{01,02,03} \frac{Q_{evap,ars}}{COP_{ars}} \tag{11}$$

$$Q_{evap,ars} = F_{in,ars} C_{p,water} (T_{in,ars} - T_{out,ars}) \tag{12}$$

where COP_{ars} is the centralized ARS's COP, $PC_{pump,ars}$ is the power consumption by ARS pump operation, $Q_{evap,ars}$ is the heat required for ARS evaporator, $c_{p,water}$ is the specific heat capacity of water, $Q_{abs-con,ars}$ is the heat required for absorber and condenser, $F_{cw,ars}$ is the cooling water flowrate for absorber condenser, $T_{cwo,ars}$ is the ARS cooling water outlet temperature and $T_{cwi,ars}$ is the ARS cooling water inlet temperature.

4. Case Study

The case study used in this paper involves three chemical processing plants with various amount of waste heat; the hypothetical waste heat flow rate from each plant is shown in Figure 2. The supply temperatures of WHW, WHS and WFG in the case study are taken as 95 °C, 152 °C, and 550 °C. Based on the temperature of the waste heat, single effect ARS is selected for WHW while double effect ARS is selected for WHS and WFG (Xu et al., 2015). It is further assumed in this work that a fixed minimum chilled water supply temperature by ARS is 5℃. The sinks and sources flow rates and temperature data are obtained from Leong et al. (2016). A mixed integer non-linear programming (MINLP) model is developed to synthesize an inter-plant WHRN with a centralized cooling hub. LINGO v16.0 optimization software with global solver is used to solve the formulated MINLP models.
The conventional layout of chilled water generation using waste heat without the centralized cooling hub is shown in Figure 2. The layout exhibits the phenomena of an oversupply of waste heat in Plant A (excess waste heat is purged) as compared to its neighbouring plant B with insufficient waste heat (chilled water deficit is satisfied by VCRS). Additionally, purge of waste heat can also be observed in Plant C where the waste heat amount for WHW is insufficient to invest in an ARS, this will be further explained in section 4.2. In this work, a centralized cooling hub is being explored to optimize the waste heat recovery as shown in Figure 1. Through visual comparison, apart from efficiently recovering the overall waste heat (no purge is observed in Figure 1), the implementation costs of the WHRN is greatly reduced from five ARS and two VCRS (Figure 2) to three ARS

and one VCRS by forming a centralized cooling hub (Figure 1). Therefore, the proposed network in Figure 1 is selected for the case study.

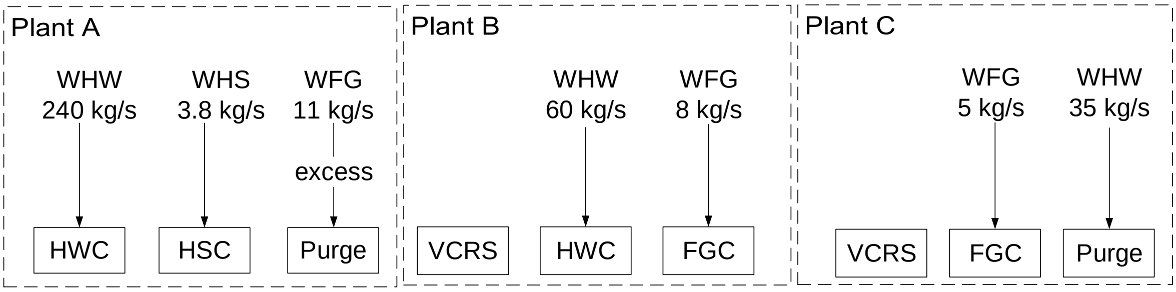

Figure 2: Waste heat and refrigeration system superstructure representation without centralized cooling hub

4.1 Results and discussions

This section includes the result comparison between the base case and the proposed network for the case study (Figure 1). Additionally, discussion is made based on the overall CCWN for the case study. Lastly, sensitivity analysis is carried out to determine the minimum value for ARS investment and to evaluate the trend of overall TAC against various waste heat flow rate.

Table 1: Comparison of results between base case and case study

Parameters	Base case	Case study
TAC (USD)	5,900,000	4,400,000
Total energy consumption (kWh)	11,620	37,409
Overall COP	4.00	1.17

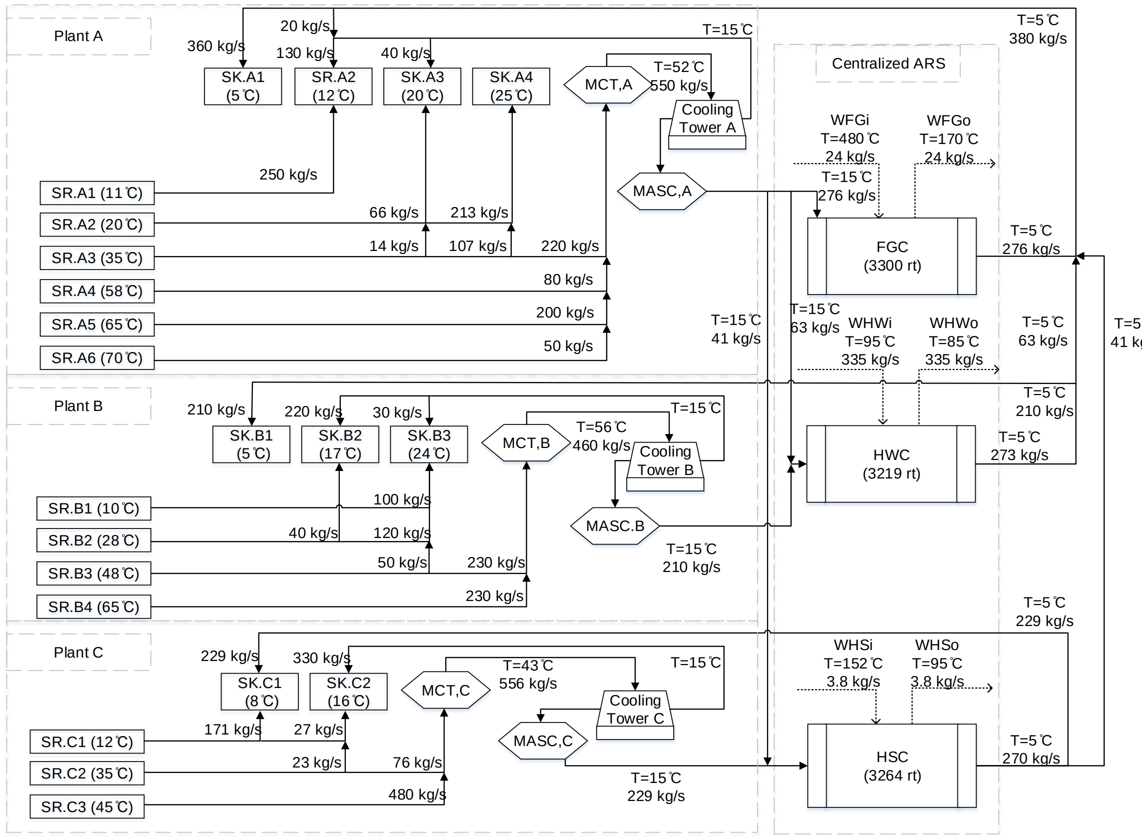

Figure 3: Overall network for the case study

According to Table 1, the TAC percentage reduction of case study compared to base case is 26 %. CCWN integrated with ARS has higher energy consumption because ARS has lower COP as compared to VCRS. The overall COP is calculated using the average COP value of the chillers present in the centralized cooling hub. Despite having lower overall COP, the case study has lower TAC because the utilization of waste heat shows remarkable savings in electricity consumption. Therefore, it will be selected for sensitivity analysis.

Based on Figure 3, free cooling by CT is utilized to reduce the cooling load of chiller refrigeration system. This is because the capital and operating cost for chiller is significantly greater than that for CT. The main difference between base case and case study is the configuration of chillers in the centralized cooling hub. Three units of VCRS were used for the base case, while one ARS unit was used for each type of waste heat in the case study, giving a total of three ARS unit. The capacity of each ARS was almost fully utilized as the maximum capacity for one chiller (ARS/VCRS) is 3,300 refrigeration t. Although VCRS is available in the superstructure for the proposed network, it is not selected in the optimum configuration because ARS is more cost effective and the amount of waste heat available is sufficient to sustain the overall chilled water capacity for the entire EIP. As compared to Figure 2, the network became less complex when centralized VCRS-ARS was used, as waste heat sharing resulted in total elimination of VCRS and reduction in ARS unit. The symbiotic relationship also improved the overall network reliability as waste heat sharing allows the plants to backup each other in case of process changes.

Figure 4 shows the sensitivity analysis performed on the case study to investigate the effect of waste heat availability (by varying the waste heat flow rate) on the chiller configuration. The analysis focused on one waste heat type at a time. For example, WHW and WFG were set to zero while varying the WHS flow rate and the total number of VCRS and ARS unit was recorded. There is a minimum flow rate for each waste heat, where the electricity cost saving from utilizing waste heat starts to overwhelm the capital investment cost of ARS, or else it will result in higher TAC compared to VCRS. This is because ARS has a higher capital cost compared to VCRS. The minimum value is 1 kg/s for WHS, 5 kg/s for WFG and 100 kg/s for WHW. According to Figure 4, TAC is much lower for the points where the capacity of ARS and VCRS unit was fully utilized (i.e. 2 VCRS and 1 HSC, 2 VCRS & 1 FGC, 2 VCRS & 1 HWC). This trend can be explained using the capital cost constraints for the equipment. The capital cost for equipment is divided into initial cost and incremental cost, investing in large equipment is more cost effective compared to investing in several equipment with similar total capacity, as this will increase the initial capital cost. In short, this analysis serves as an important tool to predict the optimum waste heat required for ARS operation.

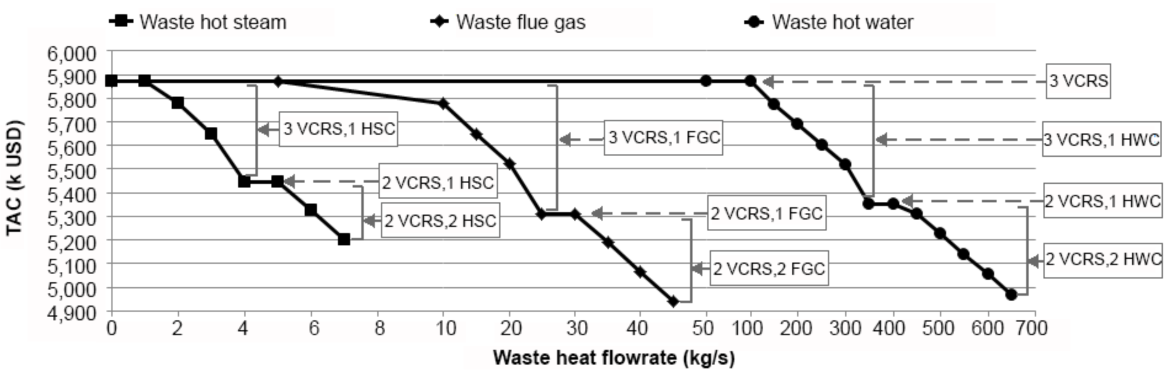

Figure 4: Sensitivity analysis for the case study

5. Conclusion

In this paper, CCWN superstructure integrated with VCRS and/or ARS was developed. The superstructure was formulated and solved as MINLP models. Optimization was performed on the model in order to seek for the configuration that gives minimum TAC while being able to fulfil the chilled water supply capacity in the CCWN. Through result comparison, CCWN integrated with ARS showed better economic performance as it had the lowest TAC. The optimized case study showed 26 % lower TAC as compared to the base case. This paper also analysed the centralized cooling hub refrigeration capacity, chiller unit quantity and waste heat amount required by ARS, which are important for chiller selection, equipment sizing and cost estimation. The main contribution of this paper is to show that the integration of VCRS-ARS into CCWN increases the cost saving in an EIP, reduces network complexity and brings the industries closer to clean production. As for future improvement, studies can be performed on further utilization of waste heat. For instance, the flue gas outlet from ARS can be sent to economizer of another EIP which consists of Combined Heat and Power to preheat the water entering hog boiler. During decision making in an EIP, doubts may arise in the industries regarding the integrity of the decision. Game Theory approach can be carried out to study the individual payoff in order to enhance the satisfaction level of each industry in forming the integrated waste heat recovery within an EIP.

Acknowledgments

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