Applied Energy 131 (2014) 307–322

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Integrated design and optimization of technologies for utilizing low grade heat in process industries

Dong-Hun Kwak, Michael Binns, Jin-Kuk Kim *

Department of Chemical Engineering, Hanyang University, Wangsimni-ro 222, Sungdong-gu, Seoul 133-791, Republic of Korea

HIGHLIGHTS

- Implementation of a modeling and design framework for the utilization of low grade heat.
- Application of process simulator and optimization techniques for the design of technologies for heat recovery.
- Systematic and holistic exploitation for the recovery of industrial low grade heat.
- Demonstration of the applicability and benefit of integrated design and optimization framework through a case study.

ARTICLE INFO

Article history:
Received 28 September 2013
Received in revised form 27 May 2014
Accepted 18 June 2014
Available online 10 July 2014

Keywords:
Low grade heat
Process integration
Optimization
Energy efficiency

ABSTRACT

The utilization of low grade heat in process industries has significant potential for improving site-wide energy efficiency. This paper focuses on the techno-economic analysis of key technologies for energy recovery and re-use, namely: Organic Rankine Cycles (ORC), boiler feed water heating, heat pumping and absorption refrigeration in the context of process integration. Process modeling and optimization in a holistic manner identifies the optimal integrated configuration of these technologies, with rigorous assessment of costs and technical feasibility of these technologies. For the systematic screening and evaluation of design options, detailed process simulator models are evaluated and optimization proceeds subject to design constraints for the particular economic scenarios where technology using low grade heat is introduced into the process site. Case studies are presented to illustrate how the proposed modeling and optimization framework can be useful and effective in practice, in terms of providing design guidelines and conceptual insights for the application of technologies using low grade heat. From the case study, the best options during winter are the ORC giving a 6.4% cost reduction for the ideal case with low grade heat available at a fixed temperature and boiler feed water heating giving a 2.5% cost reduction for the realistic case with low grade heat available at a range of temperatures. Similarly during summer boiler feed water heating was found to be the best option giving a 3.1% reduction of costs considering a realistic waste heat temperature profile.

1. Introduction

Increasing the energy efficiency of industrial processes is an important issue due to the rising cost of fuel and regulations related to carbon emissions. One method to increase energy efficiency is through utilization of low grade heat. Large quantities of low grade heat with temperatures between ambient and 523 K are often wasted. This wasted heat has the potential to generate electricity, to generate some cooling duty or to be used as an addition heat source with the introduction of new equipment. An attractive feature of low grade heat utilization is that it does not require additional fuel or emit any additional greenhouse gases. Moreover the temperature ranges of low grade heat are similar to those produced by renewable energy heat sources (e.g. solar heat and geothermal energy) so it is also possible to apply the low grade heat utilization methods to renewable energy.

To integrate these recovery technologies with a site pinch technology is commonly used [1–4]. This involves analysis of the unit processes using composite curves and using the pinch approach to determine how these heat recovery options should be used. In particular the site profiles generated can be used to analyze the site energy system to identify available waste heat which can be integrated with heat recovery equipment [3].

Waste heat can be recovered and re-used in many different ways using different pieces of equipment either to generate electricity or to provide an additional source of heating or cooling.

* Corresponding author. Tel.: +82 (0)2 2220 2331.
E-mail address: jinkukkim@hanyang.ac.kr (J.-K. Kim).

http://dx.doi.org/10.1016/j.apenergy.2014.06.037
0306-2619/

Nomenclature

A	area (m^2)
C_{hx}	heat exchanger cost ($)
C_c	compressor cost ($)
C_t	turbine cost ($)
C_p	pump cost ($)
C_d	column cost per tray ($)
C_{pipe}	pipe cost per meter ($)
$C_{A,fuel}$	fuel cost per year ($/yr)
$C_{A,electricity}$	electricity cost per year ($/yr)
$C_{A,water}$	cooling water cost per year ($/yr)
$C_{A,capital}$	annualized capital cost ($/yr)
C_{TAC}	total annual cost ($/yr)
D_d	column diameter (m)
D_p	pipe diameter (m)
F	liquid volume flowrate (m^3/s)
h_i	enthalpy of ith state point (kJ/kg)
LMTD	log mean temperature difference (K)
m	mass flowrate (kg/h)
Q	heat load in heat exchanger (MW)
Q_{in}	heat input (MW)
Q_{out}	heat output (MW)
$T_{i,ORC}$	temperature of ith stream in ORC (°C)
$T_{i,HP}$	temperature of ith stream in heat pump (°C)
$T_{i,AR}$	temperature of ith stream in absorption refrigeration (°C)
U	overall heat transfer coefficient (W/m^2 K)
W_c	electricity used in compressor (kW)
W_p	electricity used in pump (kW)
W_t	electricity generated in turbine (kW)
η_c	adiabatic efficiency of compressor
ηp	adiabatic efficiency of pump
η_t	adiabatic efficiency of turbine
η_{ORC}	overall efficiency of ORC
ρ	fluid density (kg/m^3)

To generate electricity the waste heat can be used to drive a Rankine cycle. Although given the low temperature of the waste heat it is considered to be more appropriate to use an Organic Rankine Cycle (ORC) which uses an organic material as working fluid [5]. This is because conventional steam-powered cycles have lower efficiency when using low temperature waste heat [6,7]. A number of articles have considered optimization of the working fluid or the working fluid mixture [6–9] although only a few of these authors consider the capital costs and none of these works calculate the overall costs of the ORC integrated with a site. Some authors also considered the use of Kalina cycles using mixtures of ammonia and water as the working fluid to generate electricity [7].

For generating an additional heat source the options include either utilizing a heat pump to increase the temperature of the waste heat or simply using an additional heat exchanger to re-use the heat directly (e.g. for boiler feed water heating). For example Matsuda et al. [4] demonstrated the fuel savings which could be achieved by connecting a heat pump to a large scale petrochemical site. Using pinch analysis they show that fuel requirements can be reduced by 17.8 MW while an additional 3.4 MW of power was required for the heat pump (an overall reduction of 9.3 MW, assuming a power generation efficiency of 39.6%). Alternatively this waste heat can be used directly for boiler feed water heating in the site or in a district heating system off the site assuming there is sufficient demand close to the site.

An alternative use of waste heat is to generate cooling duty using an absorption refrigeration cycle. This process has been described in detail by Srikhirin et al. [10] and assuming there is a demand for cold utility this can reduce or eliminate the power requirements of an existing cooling system. For example Kalinowski et al. [11] show that using 9 MW of waste heat 5.2 MW of cooling duty can be generated at an LNG plant which reduces the electric power requirement of the plant by 1.9 MW.

In some cases [6,9,12] the internal parameters inside individual heat recovery technologies are optimized in order to maximize the efficiency or minimize the costs. For example Dai et al. [6] optimize the working fluid, pressure and inlet temperature of the turbine inside an Organic Rankine Cycle. Also, while Victor et al. [7] have focused on optimization of the working fluid composition they have repeated this optimization at several different turbine inlet temperatures giving an extra level of detail.

Optimization of internal parameters and conditions (e.g. stream temperatures) is particularly important because the cost and size of the units involved are very sensitive to these values. Therefore, to find an optimal solution (i.e. the most profitable point), methodology for determining the quantity and quality of available low grade heat and optimization of the waste heat recovery system is required.

A number of studies have compared different options for re-using waste heat [7,13–17] including discussion of the benefits and limitations of each heat recovery technology. However, with the except of the work of Kapil et al. [14] these authors do not calculate energy costs for comparison of the different low grade heat recovery techniques. In terms of the capital costs Law et al. [15] gives qualitative comparisons indicating that the direct re-use of waste heat through a heat exchanger is preferable to other options such as heat pumps, Rankine cycles or cooling systems because the latter options all require more pieces of equipment which suggests higher capital costs for installation. They also point out that capital costs increase if the heat sink using the low grade heat is further away from the site. Kapil et al. [14] give equations for calculating capital costs but their final comparison is based only on the costs of energy. As the economic feasibility of each method can be underestimated due to the oversizing of equipment, care must be taken for economic analysis and comparisons should consider both capital and energy costs to determine which options are feasible and profitable.

Also, these comparison studies [13–16] and many of the individual waste heat recovery studies [6,7,11] do not consider the quantity and quality of waste heat available for heat recovery and they assume that the waste heat is available at a fixed temperature. However, this is not realistic as waste heat will typically be available at a range of different temperatures at different locations inside the site.

Similar trends have continued in recent years. This includes the comparative study of various heat recovery technologies used in UK industries carried out by Hammond and Norman [18], which collectively assessed on-site heat usage with heat exchangers, heat pumps, and the use of heat for supplementing refrigeration, ORC and off-site heating. Among these alternatives, the recovery of surplus heat through heat exchangers and ORC were found to be most promising options, but this analysis was limited in that it did not reflect the detailed nature of process performance and its impacts on heat recovery because thermodynamic performance was mainly evaluated with relatively simple models. However, more detailed evaluation of feasibility and techno-economic impacts for industrial