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Evaluating the potential of process sites for waste heat recovery

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HIGHLIGHTS

- Analysis considers the temperature and duties of the available waste heat.
- Models for organic Rankine cycles, absorption heat pumps and chillers proposed.
- Exploitation of waste heat from site processes and utility systems.
- Concept of a site energy efficiency introduced.
- Case study presented to illustrate application of the proposed methodology.

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ABSTRACT

As a result of depleting reserves of fossil fuels, conventional energy sources are becoming less available. In spite of this, energy is still being wasted, especially in the form of heat. The energy efficiency of process sites (defined as useful energy output per unit of energy input) may be increased through waste heat utilisation, thereby resulting in primary energy savings.

In this work, waste heat is defined and a methodology developed to identify the potential for waste heat recovery in process sites; considering the temperature and quantity of waste heat sources from the site processes and the site utility system (including fired heaters and, the cogeneration, cooling and refrigeration systems). The concept of the energy efficiency of a site is introduced – the fraction of the energy inputs that is converted into useful energy (heat or power or cooling) to support the methodology. Furthermore, simplified mathematical models of waste heat recovery technologies using heat as primary energy source, including organic Rankine cycles (using both pure and mixed organics as working fluids), absorption chillers and absorption heat pumps are developed to support the methodology. These models are applied to assess the potential for recovery of useful energy from waste heat.

The methodology is illustrated for an existing process site using a case study of a petroleum refinery. The energy efficiency of the site increases by 10% as a result of waste heat recovery. If there is an infinite demand for recovered energy (i.e. all the recoverable waste heat sources are exploited), the site energy efficiency could increase by 33%. The methodology also shows that combining technologies into a system creates greater potential to exploit the available waste heat in process sites.

1. Introduction

The process industries are responsible for 27% of global energy consumption, and annual demand for heat and electricity is expected to grow by 1.9% and 2.4%, respectively [1]. Energy-intensive process industries, such as for the manufacture of iron and steel, cement, petrochemicals, chemicals, oil and gas exploration, and pulp and paper, currently account for 69% of total industrial energy consumption [1]. In spite of the increasing demand, depleting reserves of fossil fuels and increasing energy prices, energy in the form of low-grade heat is still being wasted. Globally, the percentage of energy inputs from coal, natural gas, oil, nuclear and renewables converted into electricity, heat and transformed into another form for use in the various sectors of an economy i.e. industry, transport, building and others is 67% [1], while for the process industries in the UK, at least 40% [2] of the energy content of fuel is wasted. Using energy more efficiently could reduce demand for fuel; thereby conserving resources, reducing operating costs and reducing CO_2 emissions. Improving energy efficiency of the process industries has the potential to reduce global emissions by 44% in 2035 [3]. To this end, concepts have been developed to increase energy efficiencies in the process industries and minimise industrial demand for energy.

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Nomenclature

a	regression coefficient for absorption chiller
b	regression coefficient for absorption chiller
c	regression coefficient for absorption heat pump
COP_{AbC}	absorption chiller coefficient of performance
COP_{AHP}	absorption heat pump coefficient of performance
d	regression coefficient for absorption heat pump
ΔH	change in enthalpy (kW)
P	pressure (kPa)
Q	heat load (kW)
T	temperature (°C)
T_s	stream supply temperature (°C)
T_t	stream temperature (°C)
ΔT_{min}	minimum temperature difference (°C)
W	work (kW)

Greek letters

α	regression coefficient for organic Rankine cycles
β	regression coefficient for organic Rankine cycles
γ	regression coefficient for organic Rankine cycles
η_{real}	ORC real efficiency
η_{ideal}	ORC ideal efficiency

The concept of Pinch Analysis was introduced and applied in the process industries to maximise heat recovery in a process plant by heat exchange [4]. This concept is based on estimating thermodynamically feasible energy targets by recovering and reusing the heat energy within a process until the process is constrained or "pinched" i.e. a minimum temperature approach is reached. However, even when heat recovery within a process is maximised, some residual heat is typically rejected to cooling water or to air; depending on the pinch point, the temperature of the heat rejected could be high enough to be a valuable source of heat, or it may be too close to ambient conditions to be worth recovering.

To maximise heat recovery between processes on a site, the concept of total site analysis was developed [5]. This concept takes into account surplus and residual heat from different processes on a site using the site profiles from which the site energy demand for heating, cooling, refrigeration and power can be determined to maximise energy recovery between processes on the site. While residual heat of a suitable temperature can be used to generate steam by heat recovery, that at lower temperatures is typically rejected to ambient heat sinks.

Demand of a process (or site) for utilities, such as, steam, power, high temperature heat and cooling can be determined using Pinch Analysis for a single process or total site analysis for multiple processes on a site. A central utility system is usually designed to satisfy demand for steam and power, high temperature heat demand requires fired heating in a furnace, while cooling demand is met by a cooling water system, air cooling or a refrigeration system [6]. Utility systems are designed to generate heat and power to maximise the utilisation of the energy content of a given amount of fuel [7]. However, a major drawback with cogeneration units is the large amount of residual heat left, especially at temperatures too low for steam generation or in quantities that exceed the demand on site for process heating.

Therefore to address the problem of excessive residual heat, a methodology is introduced in Varbanov et al. [6] to improve energy utilisation by evaluating the true value of steam and saving steam through reduction in process consumption or generation of additional power. The potential to use residual heat at temperatures too low for steam generation, power generation using Rankine cycles and heat in exhaust of combustion devices such as boilers and gas turbines is not considered. Zhang et al. [8] proposed an optimisation procedure for retrofitting existing utility systems by employing heat integration within a process, between processes to recover surplus heat and low temperature heat recovery. However, the low temperature heat recovery is limited to temperatures high enough for steam power generation and boiler feed water preheating. To evaluate the potential to generate useful energy (power, heat and chilling) from the residual heat it is necessary to define the term 'industrial waste heat'.

Various definitions have been attributed to industrial waste heat. Viklund and Johansson [9] define waste heat as heat generated as a by-product of industrial processes. In this definition, the potential for heat recovery within and between processes is omitted. Ammar et al. [2] define waste heat as heat for which recovery is not viable economically, while Bendig et al. [10] defines waste heat as the sum of the exergy available in a process after heat recovery and utility integration. Both Ammar et al. [2] and Bendig et al. [10] recognise the possibility of heat recovery within a process, but neither accounts for the heat rejected from a site utility system which is designed to satisfy the process energy demand.

In this paper, industrial waste heat is defined as the sum of the residual heat rejected from the processes on a site and residual heat rejected from the site utility system designed to satisfy the energy demand, namely heating, cooling, refrigeration and power [11]. With respect to the processes on a site, waste heat is the heat rejected to cooling water and air after heat recovery within a process or heat recovery between processes on a site using Total Site Integration [5]. Therefore the scope for waste heat is defined for when a process and a site has reached their maximum potential for heat recovery. Recovering heat within a process or between processes until the process or site is pinched is relatively inexpensive and easy to implement [9]. With respect to the utility system, waste heat is the heat rejected to cooling water and air from a utility system designed to satisfy the energy demand of a site [11]. Waste heat can occur over a wide temperature range and from multiple sources in process sites, and the use of excess heat could provide a way to reduce primary energy demand.

Diverse technologies exist to recover energy in the form of power, cooling and heat from waste heat using waste heat as the primary energy source. Examples of technologies for work generation include thermoelectric generators, phase change materials, organic Rankine cycles (ORC), Kalina cycles and trilateral flash cycles. In thermoelectric generators, electricity is generated when a voltage difference occurs in a conductor because of a temperature gradient caused by the transfer of thermal energy through the material [12]. Commercially available low-temperature thermoelectric materials are up to 250 °C [13]. The generators have no moving parts, are compact, quiet, highly reliable and environmentally friendly [14]. However, relatively low efficiency has limited its use (typically around 5–10%) but they have high capability for utilising huge amounts of waste heat in an easy and simple manner [14]. Phase change materials use the expansion and contraction of a paraffin mixture as it changes from solid to liquid state to produce electricity from heat. Mechanical energy from expansion and contraction is converted into electricity in a generator [10]. The electrical efficiency is very low; 2.5–9% [15] and the technology are still in demonstration phase [15]. The Organic Rankine cycle