Energy 89 (2015) 864–873

Contents lists available at ScienceDirect

Energy

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

Low grade waste heat recovery using heat pumps and power cycles

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form
1 June 2015
Accepted 9 June 2015
Available online 8 July 2015

Keywords:
Waste heat
Compression-resorption
Heat pumps
Power cycles
Economic comparison

ABSTRACT

Thermal energy represents a large part of the global energy usage and about 43% of this energy is used for industrial applications. Large amounts are lost via exhaust gases, liquid streams and cooling water while the share of low temperature waste heat is the largest.

Heat pumps upgrading waste heat to process heat and cooling and power cycles converting waste heat to electricity can make a strong impact in the related industries. The potential of several alternative technologies, either for the upgrading of low temperature waste heat such as compression-resorption, vapor compression and trans-critical heat pumps, or for the conversion of this waste heat by using organic Rankine, Kalina and trilateral cycle engines, are investigated with regards to energetic and economic performance by making use of thermodynamic models. This study focuses on temperature levels of 45–60 °C as at this temperature range large amounts of heat are rejected to the environment but also investigates the temperature levels for which power cycles become competitive. The heat pumps deliver 2.5–11 times more energy value than the power cycles in this low temperature range at equal waste heat input. Heat engines become competitive with heat pumps at waste heat temperatures at 100 °C and above.

1. Introduction

Thermal energy or heat represents a large part of the total energy consumption, amounting 47% of world energy consumption worldwide and 37% of the energy used in OECD countries [1]. Out of this heat amount, about 43% of the energy is used for industrial applications, so it comes as no surprise that most large industrial companies are setting ambitious energy savings programs. McKenna [2] estimated the annual market potential for surplus heat from industrial processes in the UK as 36–72 PJ, while Markides [3] investigated the role of heat pumps, CHP (combined heat and power) schemes, and options for the recovery and conversion of waste heat into useful work, towards the creation of a high-efficiency sustainable energy future. The main industrial sectors accounted for in the study of McKenna [2] were: aluminum, cement, ceramics, chemicals, food and drink, glass, gypsum, iron and steel, lime, pulp and paper.

Fig. 1 has been adapted from data reported by Ammar et al. [4] to illustrate the thermal energy rejected to the environment from some major industrial sources in the UK. A significant amount of low grade waste heat is available as water from cooling towers with temperatures in the range of 45–60 °C. In particular, distillation alone is responsible for 40% of the thermal energy used in the chemical process industry [5,6]. Distillation has low thermodynamic efficiency, requiring the input of high quality energy (e.g. steam) in the reboiler – while rejecting a similar amount of heat at lower temperature, in the condenser, to the cooling water. Several HP (heat pump) concepts have been proposed to upgrade that thermal energy and reduce the consumption of valuable utilities, and under certain conditions, the energy savings of HP assisted distillation is usually around 20–50% [7].

Moussa et al. [8] reported the average availability of cooling water flows of 8 m^3/s at 35 °C (14 PJ) and 3.5 m^3/s at 60 °C (17 PJ) for the Tata Steel plant located in Ijmuiden (The Netherlands). This amount of energy is already significantly larger than the value reported in Fig. 1 for the steel industry sector alone, in UK [4]. In Europe, 1142 PJ of low temperature heat (below 100 °C) and 829 PJ medium temperature heat (at levels of 100–400 °C) are required yearly for the chemical process industry [9]. As much as 20–50% of the energy used is ultimately lost via waste heat contained in

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http://dx.doi.org/10.1016/j.energy.2015.06.030
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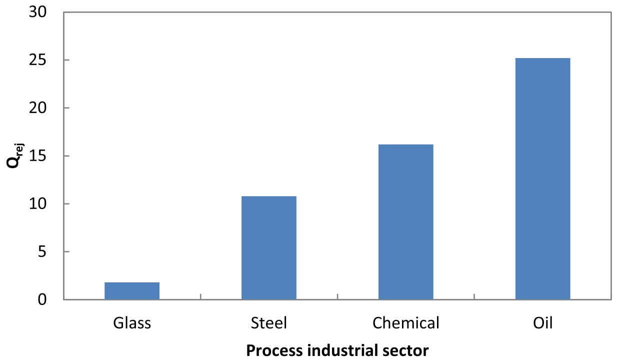

Fig. 1. Low grade thermal energy rejected from some major UK industrial sources.

streams of hot exhaust gases and liquids. Large amounts of heat contained in spent cooling water (at levels of 45–60 °C) are rejected to the environment in industrial plants (e.g. to air in cooling towers, or as waste water discharged in sea). Presently, the share of waste heat recovery contribution to the total energy usage is still negligible, in spite of the large impact potential.

Over three decades ago, Hodgett and Oelert [10] discussed the use of waste heat to drive absorption heat pump systems and compression heat pump systems. They concluded, at that time, electrically driven heat pumps are able to replace oil, but only limited energy savings are achieved compared to oil and gas fired heating systems. A review on waste heat recovery and utilization was provided by Al-Rabghi et al. [11] concluding that considerable potential exist for recovering some of the wasted energy in industrial processes and research is focused on heat exchangers utilizing heat pipes, heat engines and heat pumps. More recently, the number of publications on this topic has increased significantly. Several examples are worth mentioning here. Little and Garimella [12] assessed both sorption cycles and mechanical systems based on vapor compression for waste heat recovery applications. They found that organic Rankine cycles performed better than Maloney–Robertson cycles at equal footprint, and combined organic Rankine vapor compression cycle was more compact than absorption cycles for the same performance at high waste heat temperatures of 120 °C but slightly larger at a lower waste heat temperature of 60 °C. Ammar et al. [4] address the potential for low grade heat recovery with regard to new incentives and technological advances. Ohman and Lundqvist [13] compared power cycles driven by low temperature heat sources and provided a method to estimate power cycle performance based on heat source and heat sink temperature only. They conclude that the performance of a low temperature power cycle depends mainly on the value of electric power. Fischer [14] compared trilateral cycles with organic Rankine cycles and concluded that the trilateral cycles generally offer better performance. Ajimotokan et al. [15] show that with these cycles an efficiency of 14% is attainable at 90 °C. Recently, Hammond and Norman [16] concluded that heat pumps and low temperature heat engines are the best solutions for waste heat recovery. Most of the aforementioned research has focused on energy savings, however, no economic value was added to these savings and a comparison on economic basis is generally missing.

This study investigates the recovery and upgrade of LGWH (low grade waste heat) by using heat pumps and low-temperature heat engines. Note that LGWH is defined as the heat which is not viable to recover within the processes and it is rejected to the environment [4]. Heat pumps – such as CRHP (Compression Resorption Heat Pumps) – can be used to convert waste heat streams to process streams that are usable for heating and cooling purposes. In this way, the rest of heat available in these waste heat streams can be re-used in industrial processes. Waste heat water streams with temperatures in the range of 45–60 °C can be partly cooled down to 5 °C, and partly heated up to 90–130 °C (as shown in Fig. 2). Low temperature heat engines such as trilateral cycle engines generate valuable shaft power and cool the waste stream down by using the environment as heat sink.

If only the higher grade thermal energy is used for heating purposes – and considering that the Dutch potential is comparable to the UK situation – then 22–44 PJ could be converted into 25–59 PJ of process heat depending on the cycle operating conditions (COP (coefficient of performance) of 4–7) and availability of low grade thermal energy [4]. This corresponds to 20–35 PJ energy savings per year. Furthermore, when some plants also have a cooling requirement, the potential energy savings could be significantly larger.

2. Waste heat utilization in industry

Throughout the years, the district heating has advanced from steam systems to pressurized water systems. Initially, the required feed temperature was 120 °C with return temperature of 70 °C [17], but newer systems can operate at a feed temperature of 90 °C with return temperature of 40 °C, while low energy houses can even operate at a feed temperature of 55 °C with return temperature of only 30 °C [18]. In the industry, water streams of similar conditions are available, at the same temperature range as the return streams from the district heating.

An interesting case for industrial plants is not only the reuse of their own cooling water system, but also the return streams from district heating, as a heat source where waste heat is delivered at 40–60 °C. Such a water stream can be split in two streams: one which can be cooled down to form a cold utility stream and another one that can be heated up to be used as a warm utility stream. Fig. 2 illustrates the concept of the proposed system that can split a cooling-water return stream into a hot and cold utility stream by using a compression-resorption heat pump – with the hot to cold ratio depending on the coefficient of performance COP/(COP-1). Since it is not feasible to deliver water at temperatures below 0 °C (due to freezing) and some margin for control is also required, we select here for practical purposes a temperature of 5 °C as process temperature at the desorber inlet.

The systems selected and investigated hereafter are based on heat pumps – CRHP (compression-resorption heat pumps), VCHP (vapor compression heat pumps) and TCHP (trans-critical heat pumps) – as well as low-temperature heat engines such as Kalina, ORC (Organic Rankine Cycle) and TLC (trilateral cycle) engines for power generation. Chua et al. [19] discussed already opportunities to improve the performance of heat pumps, and according to their study up to 80% improvement in heat pump efficiency can be obtained by using alternative compressors or active cooling of the compressor. In the present work, we also suggest the application of a wet compressor and using large temperature glides for CHRP to further improve the HP efficiency. Most research involving the heating and cooling of water streams with CRHP heat pumps are focused on Osenbrück cycles with solution pumps and/or limited temperature glides [20–24]. The wet compression cycle is assumed to operate under conditions which should result in the best efficiency, at a vapor quality of 1 [25,26].

The ultimate goal of this study is to identify the potential to reduce the energy used in the industry, by recovering the waste heat from spent cooling-water and upgrading it to process heat or electricity by using heat pumps or low temperature heat engines. This study also investigates the waste heat temperature level for which heat engines become the most attractive option. The particularities of different technologies and the modeling