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A decision support system for waste heat recovery in manufacturing

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ABSTRACT

One third of energy consumption is attributable to the industrial sector, with as much as half ultimately wasted as heat. Consequently, research has focused on technologies for harvesting this waste heat energy, however, the adoption of such technologies can be costly with long payback time. A decision support tool is presented which computes the compatibility of waste heat source(s) and sink(s), namely the exergy balance and temporal availability, along with economic and environmental benefits of available heat exchanger technologies to propose a streamlined and optimised heat recovery strategy. Substantial improvement in plant energy efficiency together with reduction in the payback time for heat recovery has been demonstrated in the included case study.

1. Introduction

Energysecurity is of significant concern for governments, industry and the public because of the increasing level of consumption, depletion of resources and its known contribution to climate change. Global energy demand is expected to increase by 50% in 2040 compared to today's levels [1]. Of this energy consumption, the manufacturing sector is particularly important since it is directly and indirectly responsible for one-third of global energy use [2]. Industrial heating or heat related treatment is one of the largest components of energy demand, and in the UK, accounts for about 72% of industrial energy use as depicted in Fig. 1 [3]. Of this demand two-thirds can be attributed to low and high temperature processes [4].

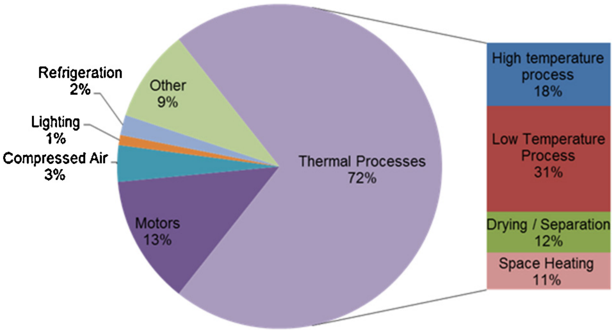

Fig. 1. Energy consumption in UK manufacturing industry [4].

Rising costs of energy along with severe targets for the reduction of greenhouse gas emissions have led to an impetus towards efficiency improvements in industry. In the short to medium term, the reduction in primary energy demand is reported to be more cost-effective than implementation of renewable energy technologies [5].

Consequently numerous research activities have sought to improve energy efficiency through methods and tools for energy minimisation management [6,7]. Limited research has been reported on assessing the appropriateness of a specific technology for a particular industrial application, although a number of researchers have identified suitability of technologies for waste energy recovery [8] and methods for assessing their environmental benefits and payback time [5,9,10]. In particular, waste heat may be used for heat pumps [11], or absorption refrigerators [12]. Moreover, waste heat may be converted into electricity [10].

This paper presents a framework and an associated decision support tool specifically focused on waste heat recovery as an input to processes where heat is required within the same facility.

2. Decision support tool for waste heat energy recovery

The WHER framework consists of four steps that aim to define a process for the identification and matching of waste heat sources and potential sinks within a manufacturing facility as shown in Fig. 2 and described below.

2.1. Step 1: waste heat survey

Waste heat survey, aimed at the identification of sources and sinks of waste heat within a manufacturing environment from both the plant and process perspectives, is carried out using either invasive techniques, i.e. thermometers, Resistor Temperature Detectors (RTDs) and thermistors, as well as non-invasive devices (infrared thermography). Flow rates are measured using a range of flowmeters and flow sensors can be used according to the types of media involved (see Fig. 3). The output from this survey often highlights a limited number of opportunities to recover large

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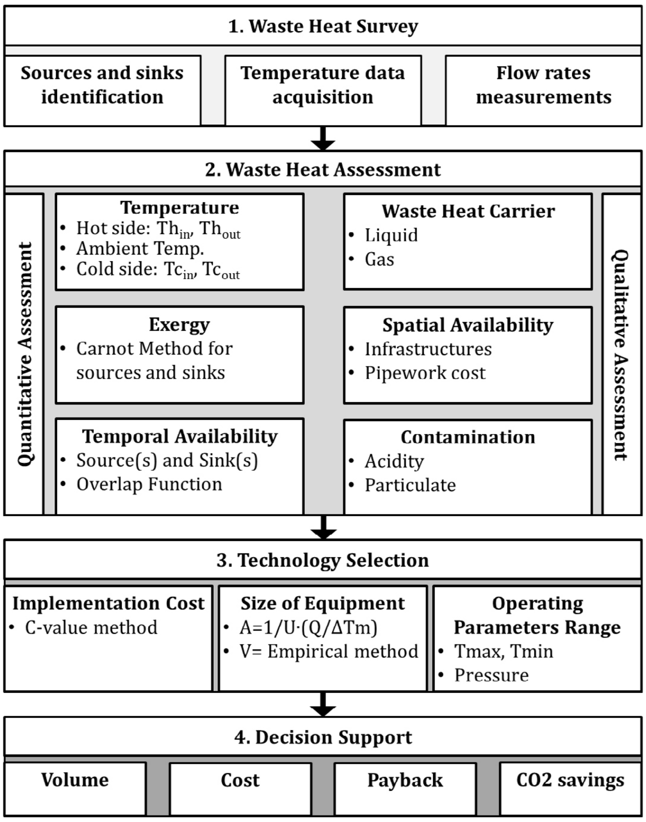


Fig. 2. Overall framework scheme.

quantities of waste heat within a facility using a number of specific parameters such as:

- Range and number of heat sources and sinks.
- Temporal information in terms of time window (hour, day or week) and time resolution (seconds, minutes, hours).
- Th_{in}, Th_{out}, T_{amb} (inlet and outlet hot medium and ambient temperature, respectively) and the flow rate (m^3/s) for the source(s).
- Tc_{in}, Tc_{out} (inlet and outlet cold medium temperature, respectively) and flow rate (m^3/s) for the sink(s).

The data generated by this survey is used by the subsequent steps in WHER for the quantitatively and qualitatively assessment of waste heat and selection of appropriate technologies to recover this energy.

2.2. Step 2: quantitative and qualitative assessment of waste heat

In order to quantitatively evaluate waste heat in a manufacturing environment, the following parameters are utilised.

2.2.1. Temperature

Clearly, the heat transfer and recovery can be enabled only if the waste heat source temperature is higher than the heat sink temperature. Hence, the magnitude of the temperature difference between the heat source and sink is an important determinant of the quality of waste heat, along with the heat transfer rate per surface area unit, and the maximum theoretical efficiency of converting thermal energy from the heat source to another form of energy, i.e. mechanical or electrical.

2.2.2. Exergy

The exergy is that part of energy that is convertible into all other forms of energy. The common energy analysis methods ignore the degradation of energy quality, and therefore exergy analysis is required to distinguish between recoverable and non-recoverable energy. The exergy can be calculated as outlined in publication by Taheri et al. [13] and formulated in the Eq. (1).

$$\text{Exergy} = m \cdot c_p \cdot \Delta T \left(1 - \frac{T_{amb}}{T}\right) \tag{1}$$

where m is the mass flow rate (kg/s), c_p is the stream specific heat capacity (kJ/kg K), ΔT is the temperature difference between the hot and the cold streams, T_{amb} is the ambient temperature and finally T is the measured temperature.

The exergy analysis is utilised to identify and quantify the heat energy loss and calculate the recoverable energies for each process [14].

2.2.3. Temporal availability for sources and sinks selection

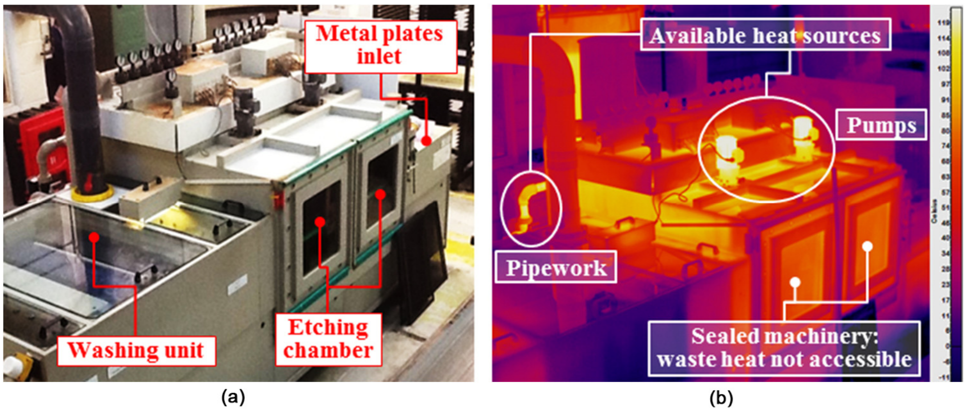
One of the key factors in maximising the potential of energy recovery is the consideration for temporal availability for sources and sinks. A methodical approach is used to undertake source and sink selection. This procedure for evaluating the best source and sink matchup using exergy and temporal availability analysis starts with listing of all the possible combinations of sources and sinks. For each combination, the exergy availability from the source(s) and exergy demand from the sink(s) are computed using the Carnot Method [13] and plotted according to the time window and resolution defined by users.

The next step is the computation of the overlap function $O(t)$ between sinks and sources, which is defined as:

$$\begin{aligned} O(t) &= \text{Exergy}_{\text{sink}}(t) \quad \text{if} \quad \text{Exergy}_{\text{sink}}(t) < \text{Exergy}_{\text{source}}(t) \\ O(t) &= \text{Exergy}_{\text{source}}(t) \quad \text{if} \quad \text{Exergy}_{\text{sink}}(t) \geq \text{Exergy}_{\text{source}}(t) \end{aligned} \tag{2}$$

This operation is repeated for all of the possible combinations of sources and sinks.

Finally, the Recovery Index (RI), defined as the ratio of areas under the Overlap function and the Source exergy curves, is used for ranking the temporal availability. In this research, the values of RI > 0.5 are only considered for heat recovery. Given amount of heat flow, ambient temperature, and temperature difference between hot and cold streams, the material properties library in MATLAB® is accessed to supply physical properties (i.e. density, specific heat capacity) for selected stream media type. Similarly, qualitative



(a) (b)

Fig. 3. Identification of waste heat hotspots in a chemical etching production line (a) using an infrared camera (b).