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Research Paper

A knowledge-based system for low-grade waste heat recovery in the process industries

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HIGHLIGHTS

- A knowledge-based system has been developed.
- System database includes heat exchangers, heat pumps and organic Rankine cycles.
- System results include technical, economic and environmental considerations.
- A case-study is shown, highlighting successful demonstration of the system.

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ABSTRACT

The rising cost of energy, combined with increasingly stringent legislation to reduce greenhouse gas emissions is driving the UK process industries towards increasing energy efficiency. Significant gains can be made in this sector by recovering low-grade waste heat as up to 14 TWh per annum (4% of total energy use) of the UK process industries' energy consumption is lost as *recoverable* waste heat. Substantial recovery of this would have economic benefits of the order of £100s of million/year and environmental benefits of 100s of thousands of tonnes of carbon dioxide equivalent per year. A similar situation is envisaged in other industrialised countries.

This paper describes the development of a knowledge-based system for the selection and preliminary design of equipment for low-grade waste heat recovery in the process industries. The system processes commonly available plant data to select the most appropriate technology for waste heat recovery from a range of programmed options. Case-study testing shows that the system can successfully select and design viable solutions for waste heat recovery from a range of options, producing designs which are economically, environmentally and technically feasible.

1. Introduction

Energy use in industry is becoming increasingly scrutinised for a variety of reasons. Firstly, the rising cost of both electricity and fossil fuel resources is leading to ever-increasing utility expenditure which can be a severe constraint in the current uncertain financial climate. Secondly, government legislation often inflicts ambitious targets for greenhouse gas reduction, such as the Climate Change Act of 2008 [1] in the UK which aims for an 80% reduction in greenhouse gas emissions between the years 1990 and 2050.

Significant gains can be made in these areas by recovering low-grade waste heat (<260 °C [2]). Reay and Morrell [3] surveyed the potential for low-grade waste heat recovery (WHR) and found that 11.4 TWh of *recoverable* waste heat is emitted to the environment in the UK processing sector. McKenna and Norman [4] used a spatial modelling technique to predict the potential for low-grade waste heat recovery and found it to be 14.4 TWh, a reasonable agreement with the prediction of Reay and Morell. Law et al. [5] estimated that the potential cost savings for waste heat recovery (via reduction in utility bills) was up to £285 m/year and the potential greenhouse gas reductions were up to 2093 ktCO_2eq/year depending on the methods of waste heat recovery employed.

Methods for identifying potential heat sources for waste heat recovery and heat integration are well established, beginning with the work of Linhoff et al. [6] who originally suggested the concept of PINCH methods for heat integration. These ideas have been further researched to incorporate complex algorithms for matching of sources and sinks [7], batch processing [8], heat pumps [9] and "cross-border" integration [10].

Various software packages have also been created utilising the pinch methodology including the EINSTEIN expert system [11] which also incorporates renewable primary energy sources, the GREENFOODS [12] package which specifically targets the food sector

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and large commercial packages such as the Aspen Energy Analyser [13].

However, little work has been done in the area of specific equipment selection. Heat integration methods are almost exclusively based on waste heat recovery via shell-and-tube heat exchanger with no consideration of process conditions or optimal heat exchanger design. Furthermore, pinch methods which have been modified to include heat pumps *etc* do so only on an energy balance basis, and do not consider practical aspects of design such as working fluid selection.

There is some existing literature discussing the benefits and drawbacks of various waste heat recovery methods. For example, Law et al. [4] discuss methods of WHR in the UK food industry, Amon et al. [14] discuss WHR in the Californian tomato paste industry, Ammar et al. [15] discuss WHR in the UK process industries and Hammond & Norman [16] discuss WHR in UK industry. However, while papers such as these can provide an indicative assessment of overall potential for utilisation of WHR equipment, such an analysis cannot accurately identify site-level opportunities. Hence, individual case-studies must be addressed by somebody with suitable knowledge of WHR technology, most commonly a consulting engineer.

Furthermore, confusion often exists regarding selection of the *most appropriate* WHR equipment when, superficially, two or more options appear to be equally suitable. This is particularly problematic when complex solutions such as organic Rankine cycles are required. For example, Law et al. [17] discuss the relative merits of high temperature heat pumps and organic Rankine cycles for waste heat recovery in the chemicals industry, and Walsh and Thornley [18] who discuss the merits of a waste heat boiler and an organic Rankine cycle for WHR in the coke industry. In both cases, the *final* decision regarding which technology is more suitable is dependent on the aims of the individual site in question, and no overriding theme is present.

This paper presents the development of a knowledge-based system (KBS) for low-grade waste-heat recovery in the process industries with a specific focus on the non-bias selection of the most appropriate equipment on an individual case-study basis. The system operates as follows (also depicted in Fig. 1):

1. User identifies waste heat source and potential waste heat sink (if available)
2. User inputs data for waste heat source, heat sink (if available) and general plant data
3. System selects *available* methods of waste heat recovery (*i.e.* methods which are both technically feasible and meet the needs of the plant)
4. System produces preliminary design of *available* equipment, including economic and CO_2 reduction data
5. *Available* equipment is ranked according to user-defined specification (capital cost, payback time or CO_2 reduction)

The system aims to provide a non-bias consultancy tool for use in the preliminary assessment of waste heat recovery technology in the process industries. It is hoped that the system will encourage the uptake of WHR projects by removing the confusion and need for expert consultancy from the preliminary assessment of equipment suitability.

2. Methodology

2.1. Equipment data base

The knowledge-base (KB) of equipment is selected according to the following scope:

1. The system must include a variety of waste heat recovery techniques: *i.e.* options for heat transfer, heat conversion and heat upgrade in order to accommodate a wide-range of possible scenarios
2. The system must include technologically viable results: *i.e.* only include technologies which have been proven on an industrial scale
3. The system must only include economically viable results: *i.e.* only include technologies which have been proven to show acceptable pay back periods (less than 5 years)

Table 1 below shows the equipment selected for inclusion in the KB.

Table 2 expands on the various types of heat exchangers included in the system and provides data and a brief discussion

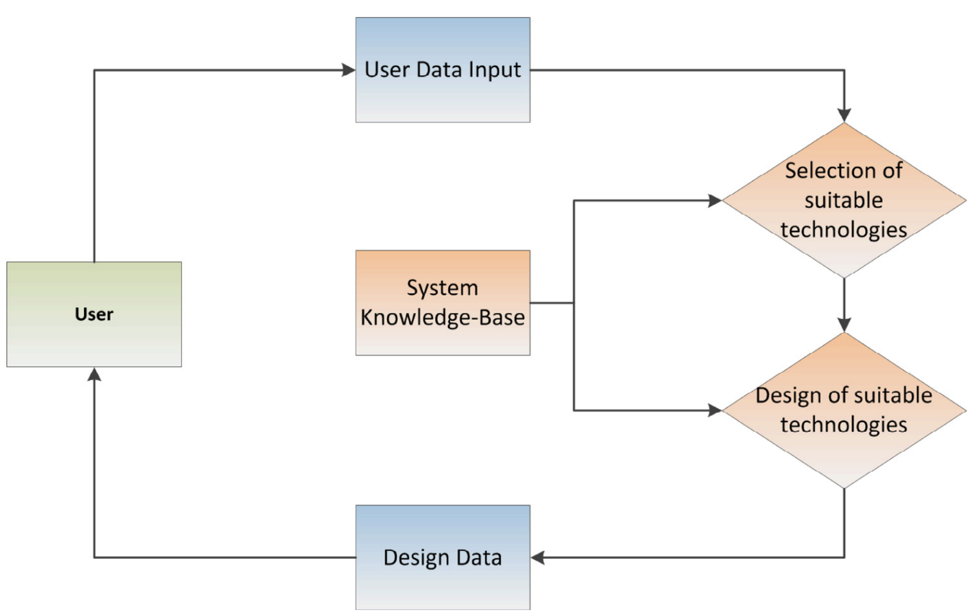

Fig. 1. Basic schematic of the knowledge-based system.