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Modelling and screening heat pump options for the exploitation of low grade waste heat in process sites

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HIGHLIGHTS

- Explicit thermodynamic models proposed for heat upgrade technologies.
- Novel system oriented criterion introduced to screen technology options.
- Diverse temperatures and quantity of waste heat sources and sinks accounted for.
- Methodology developed to apply the criterion for heat pump analysis in process sites.
- Case study presented to illustrate application of the proposed methodology.

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ABSTRACT

The need for high efficiency energy systems is of vital importance, due to depleting reserves of fossil fuels and increasing environmental problems. Industrial operations commonly feature the problem of rejecting large quantities of low-grade waste heat to the environment. The aim of this work is to develop methods for the conceptual screening and incorporation of low-temperature heat upgrading technologies in process sites.

The screening process involves determination of the best technology to upgrade waste heat in process sites, and the combination of waste heat source and sink temperatures for a technology. Novel simplified models of mechanical heat pumps, absorption heat pumps and absorption heat transformers are proposed to support this analysis. These models predict the ratio of the real performance to the ideal performance in a more accurate way, than previous simplified models, taking into account the effect of changing operating temperatures, working fluids non-ideal behaviour and the system component inefficiencies.

A novel systems-oriented criterion is also proposed for conceptual screening and selection of heat pumps in process sites. The criterion (i.e. the primary fuel recovery ratio) measures the savings in primary fuel from heat upgraded, taking into account power required to drive mechanical heat pumps and missed opportunities for steam generation when absorption systems are used.

A graphical based methodology is also developed for applying the PRR in process sites and applied to a medium scale petroleum refinery. Results show that applying the PRR yields 9.2% additional savings in primary fuel compared to using the coefficient of performance to screen and incorporate heat pumps.

1. Introduction

1.1. Background

The energy-intensive process industries (especially petrochemicals and refineries) account for 69% of total industrial energy consumption [1], and 45% of global carbon dioxide emissions; the majority of which are from combustion of fuel to produce heat and electricity [2]. In spite of this, around one sixth of overall industrial energy use is wasted at low temperatures (below 120 °C) [3]. Low grade waste heat is often rejected to cooling towers and stacks [3]. Large amounts of low grade heat may justify developing means of recovering it for useful purposes, even though the thermodynamic availability of the heat rejected is low [4].

Adoption of advanced technologies to upgrade low temperature heat to higher temperatures could provide considerable energy savings in industry, along with 7–12% reductions in today's global

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Nomenclature

A, B	regression coefficients for mechanical heat pump (–)
C, D	regression coefficients for absorption heat pump (–)
$COP_{AHP,real}$	absorption heat pump real coefficient of performance (–)
$COP_{AHT,real}$	absorption heat transformer real coefficient of performance (–)
$COP_{MHP,real}$	mechanical heat pump real coefficient of performance (–)
$COP_{AHP,ideal}$	ideal coefficient of performance for an absorption heat pump (–)
$COP_{AHT,ideal}$	ideal coefficient of performance for an absorption heat transformer (–)
$COP_{MHP,ideal}$	ideal coefficient of performance for a mechanical heat pump (–)
COP_{real}	heat upgrading technologies real coefficient of performance (–)
E, F	regression coefficients for absorption heat transformer (–)
HT	high temperature waste heat (°C)
HP	high pressure steam (bar)
i	temperature intervals on waste heat source and sink profile (–)
LP	low pressure steam (bar)
LT	low temperature waste heat (°C)
MP	medium pressure steam (bar)
MT	medium temperature waste heat (°C)
P	pressure (bar)
P_{COMP}	compressor outlet pressure (bar)
P_{EVAP}	evaporator pressure (bar)
PRR	primary fuel recovery ratio (–)
PRR_{AHP}	absorption heat pump primary fuel recovery ratio (–)
PRR_{AHT}	absorption heat transformer primary fuel recovery ratio (–)
PRR_{MHP}	mechanical heat pump primary fuel recovery ratio (–)
P_{sat}	steam main saturation pressure (bar)
Q	heat transfer rate (kW)
Q_{ABS}	heat released in the absorber (kW)
QAC	actual heat available (kW)
QAC_{T_i}	actual heat available in interval i on the waste heat source profile (kW)
$QAC_{T_{ri}}$	actual heat available in region r within interval i on the existing site sink profile (kW)
Q_{COND}	condenser heat duty (kW)
QCUM	cumulative heat available (kW)
$QCUM_{T_{ri}}$	cumulative heat available in region r within interval i on the existing site sink profile (kW)
Q_{EVAP}	evaporator duty (kW)
Q_{fuel}	fuel consumption in the site cogeneration system (kW)
Q_{GEN}	generator duty (kW)
$Q_{upgraded}$	useful heat released from technology options (kW)
Q_{T_i}	heat source required by technology options (kW)
$Q_{T_{ri}}$	heat sink satisfied from upgraded heat (kW)
Q_{steam}	steam produced from the site cogeneration system (kW)
$Q_{WH(1)}$	waste heat rejected to cooling water and air from the site processes and cogeneration system (kW)
$Q_{WH(2)}$	additional waste heat generated from power produced for the mechanical heat pump (kW)
T	temperature (°C)
T_{ABS}	absorber temperature (°C)
T_{COND}	condenser temperature (°C)
T_{EVAP}	evaporator temperature (°C)
T_{GEN}	generator temperature (°C)
T_{op}	steam main operating temperature (°C)
T_{SUPPLY}	waste heat source stream inlet temperature (°C)
T_{sat}	steam main saturation temperature (°C)
T_{TARGET}	waste heat source stream end temperature (°C)
VHP	very high pressure steam (bar)
W_{COMP}	compression power required (kW)
W_{PUMP}	pumping power required (kW)
$W_{produced}$	power produced from the site cogeneration system (kW)

Greek letters

η_{AHP}	efficiency factor for an absorption heat pump (–)
η_{AHT}	efficiency factor for an absorption heat transformer (–)
η_{MHP}	efficiency factor for a mechanical heat pump (–)
$\Delta Q_{fuel(1)}$	change in primary fuel consumed in the site cogeneration system (kW)
$\Delta Q_{fuel(2)}$	additional primary fuel required to provide electrical power for a mechanical heat pump (kW)
η_{cogen}	site cogeneration efficiency (–)
η_{power}	efficiency of electrical power generation for the mechanical heat pump (–)
ΔT_{min}	minimum permissible temperature difference (°C)

CO_2 emissions from fossil fuel displaced [5]. These technologies can also facilitate energy savings when direct heat recovery is infeasible. The benefits of upgrading low temperature heat depend on the temperatures, and quantities of the heat in the waste streams as well as the demand for the recovered energy [6].

Examples of commercialised technologies for low-grade heat upgrade are: mechanical heat pumps, absorption heat pumps and absorption heat transformers. Mechanical heat pumps (MHP) absorb thermal energy from low temperature heat sources in order to increase it for use in a high temperature heat sink using mechanical energy. In absorption heat pumps (AHP), the evaporation, expansion and condensation of the working fluid are similar with a mechanical heat pump. The difference is the circuit of a liquid absorbent circulating by a pump which replaces the compressor [7]. An absorption heat transformer (AHT) is a reversed absorption heat pump. They supply thermal energy at a higher temperature than the waste heat required i.e. the evaporator and absorber operate at a pressure higher than the condenser and generator [8]. Even though these technologies are mature and commercialised, uptake by industry is slow.

There are several challenges associated with incorporating heat pumping technologies in process sites. Firstly, the available waste heat occurs over a wide temperature range and from multiple sources (including the site processing units and the site cogeneration system) [9]. Secondly, there are multiple sinks to exploit the upgraded heat [9]. For example heat upgraded can reduce hot utility required by the processing units at different temperature levels. In incorporating heat pumps, it is necessary to determine the best combination of heat sources and sinks for any heat pump type, and the best heat pump to use. The coefficient of performance (COP) has been previously applied [10]; however, it neglects interactions with interconnected systems. Higher savings in primary fuel may be possible by developing a systems-oriented criterion for heat pump analysis in process sites. The third challenge relates to modelling of heat upgrading technologies. Simple models based on a constant ratio of the real to the ideal performance has been used