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Process integration of waste heat upgrading technologies

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ABSTRACT

Technologies such as mechanical heat pumps, absorption heat pumps and absorption heat transformers allow low-temperature waste heat to be upgraded to higher temperatures. This work develops a comprehensive Mixed Integer Linear Program (MILP) to integrate such technologies into existing process sites. The framework considers interactions with the associated cogeneration system (in order to exploit end-uses of upgraded heat within the system and determine their true value), temperature and quantity of waste heat sources and of sinks for the heat upgraded as well as process economics and the potential to reduce carbon dioxide (CO_2) emissions. The methodology is applied to an industrially relevant case study. Integration of heat upgrading technologies has potential to reduce total costs by 23%. Sensitivity analysis is also performed to illustrate the effect of changing capital costs and energy prices on the results, and demonstrate the model functionality.

1. Introduction and previous works

Adoption of technologies to upgrade low temperature waste heat to higher temperatures are becoming more relevant due to limitations on CO_2 emissions and depleting reserves of fossil fuels (Van de Bor and Ferreira, 2013). Examples of such technologies include mechanical heat pumps, absorption heat pumps and absorption heat transformers.

In mechanical heat pumps (MHP), waste heat vaporizes the working fluid in the evaporator, which is compressed to a higher temperature by electrical power. The working fluid is condensed and expanded in a valve, and then the cycle repeats. Different refrigerants such as ammonia and n-butane are suitable working fluids for the mechanical heat pump (Smith, 2005). A schematic is shown in Fig. 1. Absorption heat pumps (AHP) and heat transformers (AHT) are thermally activated heat upgrading technologies i.e. compression of the working fluid is achieved in a solution circuit consisting of a generator, an expansion valve, a solution pump and an absorber (Figs. 2 and 3) (Oluleye et al., 2016). The difference between AHP and AHT is that in an AHT, thermal energy required to vaporize the working fluid in the evaporator is supplied at a higher temperature than that of the waste heat required for separating the working fluid pair in the generator (Lazzarin, 1994). The most common working fluid pair for both technologies in industrial applications is water/lithium bromide (Donnellan et al., 2015). MHP, AHP and AHT could provide considerable reductions in CO_2 emissions and possible energy savings in the process industry (USDOE, 2003).

Previous research in this area focused on making heat pump systems more energy efficient (Grossman and Perez-Blanco, 1982; Romero et al., 2011), developing performance models for these technology options (Oluleye et al., 2016), and selection of working fluids (Oluleye et al., 2016; Angelino and Invernizzi, 1988). Optimal integration in existing process sites remains a challenging task (Chua et al., 2010).

In earlier work in this area, Wallin and Berntsson (1994) proposed using the grand composite curve (GCC) to guide

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Nomenclature

Sets

$i \in I$ Heat source streams
$j \in J$ Temperature intervals on heat source streams
$k \in K$ Sinks for upgraded heat
$pl \in PL$ Pressure distribution levels in the site cogeneration system
$t \in TT$ Technologies burning fuel to generate steam in the site cogeneration system

Independent variables

$mfuel_t$ Mass flow of fuel consumed by technologies in the site cogeneration system, kg/s
$mturbine_{pl}$ Mass flow of steam into a stream turbine at different pressure levels in the site cogeneration system, kg/s
$Qout^{MHP}_{i,j,k}$ Flow of heat upgraded to heat sink k, from a MHP using heat source stream i, in temperature interval j, kW
$Qout^{AHP}_{i,j,k}$ Flow of heat upgraded to heat sink k, from an AHP using heat source stream i, in temperature interval j, kW
$Qout^{AHT}_{i,j,k}$ Flow of heat upgraded to heat sink k, from an AHT using heat source stream i, in temperature interval j, kW
W_{Import} Total electrical power imported from the grid for site use, kW
W_{Export} Total electrical power exported to the grid, kW
$Y^{MHP}_{i,j,k}$ Binary variable for existence of a MHP to upgrade heat from stream i in temperature interval j to satisfy heat sink k.
$Y^{AHP}_{i,j,k}$ Binary variable for existence of an AHP to upgrade heat from stream i in temperature interval j to satisfy heat sink k.
$Y^{AHT}_{i,j,k}$ Binary variable for existence of an AHT to upgrade heat from stream i in temperature interval j to satisfy heat sink k.

Dependent variables

ACC Annualized capital cost, £/y
FC Overall site fuel cost, £/y
MC Maintenance cost, £/y
mQ^{STG} Mass flow of steam generated from heat recovered, kg/s
OC Operating costs, £/y
PER Overall revenue from electrical power export, £/y
PIC Overall cost of electrical power import, £/y
Qin Heat input into technology options from waste heat source streams, kW
Qout Useful heat upgraded, kW
Qsteam Heat flow of steam generated by burning fuel, kW
Q_{COND} Heat loss from steam condensation, kW
T_{EVAP} Evaporator temperature of heat upgrading technology, °C
T_{COND} Condensing temperature of heat upgrading technology, °C
T_{ABS} Absorber temperature of heat upgrading technology, °C
T_{GEN} Generator temperature of heat upgrading technology, °C
TAC Total annualized costs, £/y
TCO_2E Total CO_2 emissions, t/y
WaterC Overall cost of water, £/y
W_{MHP} Electrical power required by the mechanical heat pump, kW
W_{Demand} Site electrical power demand, kW
$W_{turbine}$ Total power produced from the steam turbines in the cogeneration system

Parameters

AF Annualization factor
CP Heat capacity flow rate, kW/°C
CW_{price} Specific cost of cooling water, £/kWh
DW_{price} Specific cost of demineralized water, £/kg
EC Specific equipment cost, £/kW
FEF CO_2 produced per kW of fuel consumed, kg/kWh
FP Specific price of fuel consumed, £/kWh
GEF CO_2 produced per kWh of electrical power distributed in the grid, kg/kWh
IR Interest rate
L Lower limit for technology size (basis is the useful heat upgraded), kW
LHVfuel Lower heating value of fuel consumed, kJ/kg
msteamgen Mass flow of steam generated from the site processes into the cogeneration system, kg/s
msteamuse Mass flow of steam consumed by the site processes, kg/s
n Technology life time (y)
PImp Electrical power import tariff, £/kWh
PExp Electrical power export tariff, £/kWh
Qac Actual heat available, kW
Qcum Cumulative heat available, kW
Qsteamgen Heat flow of steam generated from site processes, kW
Qsteamuse Heat flow of steam consumed by site processes, kW
RF Retrofit factor to account for installation of equipment
T_{Supply} Stream supply temperature, °C
T_{Target} Stream target temperature, °C
$T_{i,j}$ Shifted temperature in interval j on heat source stream i, °C
T_{BFW} Boiler feed water preheat temperature, °C
U Upper limit for heat upgraded, kW

Greek letters

α Regression parameter for heat upgrade technologies
β Regression parameter for heat upgrade technologies
ΔT_{MIN} Minimum permissible temperature difference, °C
η_t Energy conversion efficiency of technology t, %

Abbreviations

ABS Absorber
AHP Absorption heat pump
AHT Absorption heat transformer
BFW Boiler feed water
COND Condenser
COMP Compressor