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Economic evaluation of an industrial high temperature lift heat transformer

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ABSTRACT

Heat transformers are closed cycle thermodynamic systems which allow waste heat energy to be recycled by increasing its temperature. TAHTs (Triple stage heat transformers) are capable of increasing the temperature of supplied heat by up to ~140 °C. This paper attempts to analyse the industrial attractiveness of such cycles by conducting a case study on the potential installation of a TAHT in a small Irish oil refinery, examining various different natural gas price scenarios. The choice of waste heat energy being recycled is shown to be pivotal to the success or failure of the installation. TAHTs are demonstrated to show most benefits when applied to waste heat streams with large quantities of latent heat. The usage of more efficient and cost effective equipment instead of conventional shell and tube heat exchangers within the system dramatically increases the potential economic return from the heat transformer. At the present gas price, the capital cost of (conventional) equipment is too high to make this investment financially attractive for the current industrial example, with excessive payback periods predicted. However a return to natural gas price levels observed in 2008 and 2009 would make the unit economically viable.

1. Introduction

Vast quantities of waste heat energy are discharged to atmosphere on a daily basis by industrial applications. It has been estimated that approximately 3×10^{13} kWh of heat energy is being lost as waste every year from the US manufacturing industry alone [1]. Such figures correspond to approximately 50% of the energy input to this sector leaving in the form of exhaust gases, cooling water, heated products and from surfaces of hot equipment [2]. However although these figures represent significant quantities of a valuable resource, it is still the case that in many industrial scenarios energy recovery remains economically unfeasible. Thus the exploration of potential new technologies may serve to enhance the viability of heat recovery [2].

AHTs (Absorption heat transformers) are one such technology. These systems recover low temperature waste heat and increase its temperature to make it useful. The thermodynamic performances of such cycles have been analysed extensively in the literature, operated as SSHT (single stage) [3], DAHT (double stage) [4] and TAHT (triple stage) units [5] and although these reports show good energetic performances, their industrial implementations appear scarce. SSHTs are generally capable of recycling approximately 50% of the waste heat source by increasing its temperature by ~50 °C [3]. In turn DAHTs and TAHTs may recycle up to 35% and 25% of the waste heat energy, while increasing its temperature by ~80 °C [4] and ~145 °C [6] respectively.

To date, some studies have been conducted on the industrial application of single stage units. A self circulating pilot NaOH–H_2O heat transformer has been built and incorporated into the evaporation unit of a pulp and paper mill [7], achieving a GTL (gross temperature lift) of 23 °C, resulting in an estimated payback period of 4.4 years. Another study examined the various different methods of incorporating a SSHT into a sugar mill [8]. The results show that the inclusion of this unit reduces the plant's live steam requirements by between 11.8 and 16.4%. This study claims that a payback period of roughly 2.7 years may be achieved if the plant were operational for 8000 h a year. However it also suggests that this figure could also rise to up to 11.7 years if the operational time drops to 2500 h, exhibiting a very large sensitivity. An economic comparison between the use of a SSHT, a conventional absorption chiller and a mechanical vapour compression heat pump for waste heat recovery has been conducted using data from a major Swedish paper mill [9]. The study concludes that the use of a SSHT is inappropriate in this scenario, as the temperature of the waste heat

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Nomenclature

Economics terms

CGP	current gas price (€/tonne)
DPBP	discounted payback period of the TAHT design (years)
I	discount rate applied over the project lifetime (13%)
N	estimated TAHT lifetime (years)
NPV	net present value of the TAHT design (€)
SPBP	simple payback period of the TAHT design (years)

Temperatures

T_a	temperature of the salt solution in the absorber (K)
T_{ae1}	temperature of the salt solution in absorber evaporator-1 (K)
T_{ae2}	temperature of the salt solution in absorber evaporator-2 (K)
T_c	temperature of the condenser (K)
T_e	temperature of the evaporator (K)
T_g	temperature of the generator (equal to T_e in this study) (K)

Energy flows

Q_a	useful, high temperature enthalpy removed by a cooling stream from the absorber (W)
Q_c	enthalpy removed by a cooling stream (or generally ejected to the environment) from the condenser (W)
Q_e	enthalpy added to the evaporator by a heating stream (generally a waste heat stream) (W)
Q_g	enthalpy added to the generator by a heating stream (generally a waste heat stream) (W)

Pressures

P_0	pressure of the condenser and the generator. Equal to the vapour pressure of water at T_c (Pa).
P_1	pressure of the evaporator and absorber-evaporator-1. Equal to the vapour pressure of water at T_e (Pa).
P_2	pressure of absorber-evaporator-2. Equal to the vapour pressure of water at $T_{ae1}-dT_{Hx}$ (Pa).
P_3	pressure of the absorber. Equal to the vapour pressure of water at $T_{ae2}-dT_{Hx}$ (Pa).
COP	coefficient of performance of the TAHT
COP_{total}	total fraction of the waste heat stream energy content being recycled
dT_{abs}	the difference in temperature between the dilute streams leaving absorber-evaporator-1, absorber-evaporator-2 and the absorber and their respective saturation temperatures (K)
dT_{cond}	minimum temperature gradient maintained between ambient conditions and the condenser (K)
dT_{Hx}	minimum pinch temperature (heat transfer gradient) utilised in all system heat transfer operations (K)
FAT	factory acceptance test
GTL	difference in temperature between the absorber and the generator (K)
GTL1	difference in temperature between absorber-evaporator-1 and the generator (K)
GTL2	difference in temperature between absorber-evaporator-2 and the generator (K)
LHV	lower heating value of natural gas (J/kg)

energy is too low. A further study conducts an exergetic and exergoeconomic study on a cogeneration pulp and paper mill plant [10]. Pinch analysis shows that the inclusion of a heat transformer to preheat water prior to entering a boiler could potentially reduce the plant's steam consumption by up to 25%. The results of having installed a SSHT into a synthetic rubber plant in China show that a payback period of 2.01 years is realised due to an annual energy saving of 3.5 million Yuan [11]. The heat transformer is used to heat water from 95 °C to 110 °C in the plant, reducing its steam requirements from $2.53t_{steam}/t_{rubber}$ to $1.04t_{steam}/t_{rubber}$. This also results in a reduction of 2337 tonnes of exhaust gases from the plant each year. Zhang et al. [12] demonstrated that payback periods of 2.4 years are possible if a SSHT is incorporated into the CO_2 capture process in a coal fire plant.

A smaller number of industrial case studies have also examined the use of DAHTs (double absorption heat transformers). It is shown that the incorporation of a DAHT into craft pulping process can achieve simple payback periods of about 1.6 years [13]. The benefits of adding either a SSHT or a DAHT to a distillation column so that the condenser energy at 85 °C may be used to provide some of the required heat to the reboiler at 155 °C has also been examined [14]. The study shows that installing a SSHT can reduce the boiler requirements by between 26 and 43% at specific operating conditions, but that the DAHT can reduce the boiler requirements by 28–33% over a wide range of conditions. Ishida and Ji [15] proposed the combination of a DAHT with a HAT (humid air turbine), demonstrating that this may increase the HAT's specific work output by 7.3%.

From the above review, it may be seen that the applicability of an absorption heat transformer for waste heat recovery is strongly dependent upon the specific context. Also no industrial case studies of triple stage cycles appear to have been reported, and thus no knowledge is available to determine whether these represent an economically feasible option for inclusion in a plant.

2. Case study: an oil refinery

The oil refining industry is an extremely energy intensive sector and one which operates under tight profit margins, making it a primary candidate for energy recovery technology. This study has been conducted in conjunction with a small oil refining plant in Ireland, to determine whether the installation of an absorption heat transformer unit is a feasible option.

In general, waste heat energy may be recovered by direct heat exchange within a HEN (heat exchange network), by generating electricity using an ORC (Organic Rankine Cycle) or by increasing its temperature using either a heat pump or a heat transformer. The suitability of Organic Rankine Cycles is dependent upon the waste heat conditions and working fluid selected [16], however due to the complexities involved in grid integration and ensuring stability of electricity supply, the refinery has indicated that reuse of the waste energy as a heat source would be more desirable. Using these waste heat streams in direct heat exchange operations is not an option due to their low temperature, and thus either a heat pump or heat transformer must be used to recycle this energy. Due to their requirements for either large quantities of electricity or else a high temperature heat source, heat pumps are generally better suited to refrigeration applications, and thus not considered suitable in this refinery.