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EXAMINING THE ECONOMIC VIABILITY OF AN ABSORPTION HEAT TRANSFORMER IN ENERGY INTENSIVE INDUSTRIES

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Abstract

Absorption heat transformers are closed cycle thermodynamic systems which are capable of upgrading the temperature of waste heat energy and, allowing it to be recycled within a plant. An industrial case study is conducted which examines the economic viability of installing a triple absorption heat transformer in a small oil refinery. Particular attention is paid to determining the suitability of different waste heat streams which have been made available. In the refinery examined, two waste streams of interest have been identified; a viscous residue oil line and a condensing Naphtha stream. A relatively large increase in temperature is required by the company in order that the recycled waste heat energy may be incorporated into its existing heat exchange network (HEN), and thus a triple stage heat transformer is being designed. Results obtained during this study indicate that the physical properties of the residue oil stream make it unsuitable for use in such heat recovery technology, while the Naphtha condensation may be utilised with more favourable outcomes. Based upon the current gas price being quoted by the refinery, it is demonstrated that this Naphtha stream on its own does not contain sufficient quantities of recyclable energy to ensure that the system is capable of generating an acceptable return upon investment. The suitability of such heat recovery to larger, more energy intensive sites is highlighted however, and it is demonstrated that if the quantity of suitable energy available were to increase by a factor of two or four then the economic indicators begin to show substantially more favourable results. Thus it may be concluded that at the current low gas price, the use of a triple stage absorption heat transformer is mainly suited to larger plants with sufficient waste energy available for recycling.

Introduction

Future uncertainty regarding sources of energy supply and the increasing regulation of emissions means reducing fuel requirements is an attractive proposition for many companies. Currently, vast quantities of heat energy are being dissipated on a daily basis. It is estimated that up to 50% of the energy input to the US manufacturing industry is lost as waste heat in the form of exhaust gases, cooling water, heated products and from surfaces of hot equipment [1]. Although such figures represent large quantities of a valuable resource not many systems are currently employed in industry to combat this situation.

Absorption heat transformers (AHTs) are one such technology. These are closed cycle systems, which have the ability to upgrade the temperature of waste heat streams, and thus allow this energy to be recycled. Much work has been conducted to date analysing the thermodynamic performance of heat transformers. Single stage heat transformers are units which are capable of achieving relatively small rises in temperature such as 50˚C [2]. Generally these systems are capable of recycling up to 50% of the energy available to them [3]. Studies have been conducted which determine the optimum operating conditions of single stage systems, analysing the effect of varying internal settings has upon the quantity of energy recycled and the system's second law performance [4-10]. The most common working fluid employed in heat transformers is a lithium bromide water solution (LiBr-H_2O) due to its favourable thermodynamic properties [11]. While many other working fluids have also been examined [12-14], none of the benefits observed have been significant enough to signify a move away from LiBr-H_2O.

Double stage heat transformers are capable of achieving temperature lifts which are greater than those of single stage systems. Temperature augmentations of up to ~80˚C have been demonstrated for these systems, while allowing ~30% of the waste heat energy to be recovered [15].

In order to achieve the greater temperature lifts often required in industry, triple absorption heat transformers (TAHT) must be used however. These systems are capable of temperature lifts of up to ~140˚C, while recycling between 20-25% of the heat energy supplied [16-18].

Reported industrial applications of heat transformers appear to be relatively scarce although some case studies do exist. The industrial potential of single stage systems in the pulp and paper mill sector has been highlighted, with potential steam reductions of up to 25% reported [19]. A single stage system has also been installed in a synthetic rubber plant in China, achieving a payback period of 2 years [20]. Similarly it has been demonstrated that a double stage heat transformer may reduce the energy requirements of the boiler by 28-33% if installed in conjunction with a distillation column [21].

Thus it has been demonstrated that the installation of single and double stage heat transformers may represent a financially as well as energetically attractive option. It remains to be determined however whether triple absorption heat transformers have the same positive features. Thus this paper conducts an industrial case study which examines the waste streams available in a small oil refinery, and determines the economic performance of a potential TAHT operating in this plant. Particular attention is paid to the effect of utilising different waste heat energy sources.

Nomenclature

COP	Coefficient of performance of the TAHT
COP_{total}	Total fraction of the waste heat energy content being recycled
c_p	Specific heat capacity (W/(kgK))
D	Diameter (m)
k	Thermal conductivity (W/(m^{2}K))
v	Velocity (m/s)
α	Heat Transfer Coefficient (W/(m^{2}K))
ρ	Density (kg/m^3)
μ	Viscosity (Ns/m^2)
Economic Terms	
CGP	Current Gas Price ($/kg)
DPBP	Discounted Payback Period (years)
i	Discount rate applied over the project lifetime (13%)
N	Project Lifetime (years)
NPV	Net Present Value ($)
SPBP	Simple payback period (years)
Temperatures (in ascending order)	
T_c	Temperature of the condenser (K)
T_e	Temperature of the evaporator (K)
T_g	Temperature of the Generator (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_a	Temperature of the salt solution in the absorber (K)
Energy Flows	
Q_a	Useful, high temperature enthalpy removed from the absorber (W)
Q_c	Enthalpy ejected to the environment from the condenser (W)
Q_e	Enthalpy added to the evaporator by a waste heat stream (W)
Q_g	Enthalpy added to the generator by a waste heat stream (W)
Pressures (in ascending order)	
P_0	Pressure of the condenser and the generator (Pa)
P_1	Pressure of absorber-evaporator-1 (Pa)
P_2	Pressure of absorber-evaporator-2 (Pa)
P_3	Pressure of the absorber (Pa)

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 the Phillips 66 Whitegate oil refining plant in Ireland, attempting to determine whether the installation of an absorption heat transformer unit into their plant is a feasible option. A number of waste heat streams which are of primary interest to the company have been identified and incorporated into this design. The temperature profile of the plant is such that only relatively high temperature thermal heat may be used within the existing heat exchange network (HEN), and thus a relatively large gross temperature lift will be required from the heat transformer. Following analysis of the waste streams available, it is determined that only a triple stage system can achieve these required lifts. Thus in this paper, a triple stage absorption heat transformer (TAHT) system is designed for use in this oil refinery. Particular attention is paid to the economic performance of the unit as this has been highlighted by the company as the primary viability determining factor.

Following consultation with the oil refinery, two streams of primary interest for waste heat recovery are identified, both of which are currently being cooled by means of air-cooled heat exchangers. The first stream consists of a residue oil line which is being cooled from 179˚C to 87˚C. This stream has a mass flowrate of approximately 46.8kg/s and is currently discharging 9.56MW to atmosphere. The second stream which is to be examined consists of Naphtha vapour coming off the top of a distillation column, and being condensed in an air-cooled heat exchanger. It enters at approximately 120˚C, and leaves at 40˚C, discharging roughly 22.7MW of thermal energy.

The company has indicated that the most useful outcome would be to obtain a hot oil loop at 210˚C which can then be incorporated into their heat exchange network. Thus these waste streams shall enter the TAHT and be cooled down to a temperature slightly greater than the temperature of the evaporator and generator (to allow heat transfer), while the hot oil circulation loop (Ethylene Glycol under slight pressure) will circulate between the TAHT and the plant's HEN as shown in Figure 1. The heat transformer will not be capable of carrying out all of the required cooling on the waste heat streams, due to their low final temperatures, and thus following the heat transformer, each stream shall pass through an air-cooler which will reduce its temperature to the desired level.

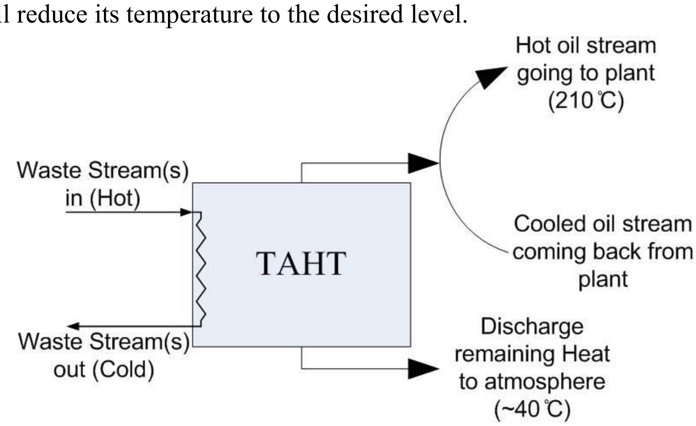

Figure 1 - Schematic of the TAHT's operation in this case study

Triple Stage Heat Transformer System Description

The TAHT design used in this study is based upon a thermodynamically optimised cycle configuration, incorporating three heat exchangers [18] as illustrated in Figure 2. In this figure all of the units are arranged vertically according to their temperature (as shown by the axis on the left hand side) to allow for easy interpretation. This system consists of 9 basic units, namely a condenser, a generator, an evaporator, two absorber-evaporators (at different temperatures), three heat exchangers (Hx1, Hx2 and Hx3), and an absorber as demonstrated in Figure 2. A heat source supplied to the generator is used to separate the more volatile component, the refrigerant, from the absorbent (in this case water and LiBr-H_20 solution respectively) by evaporation at an intermediate temperature. The refrigerant vapour then flows to the condenser where it is condensed by reducing its temperature, discharging its latent heat to a low temperature heat sink (generally to atmosphere).

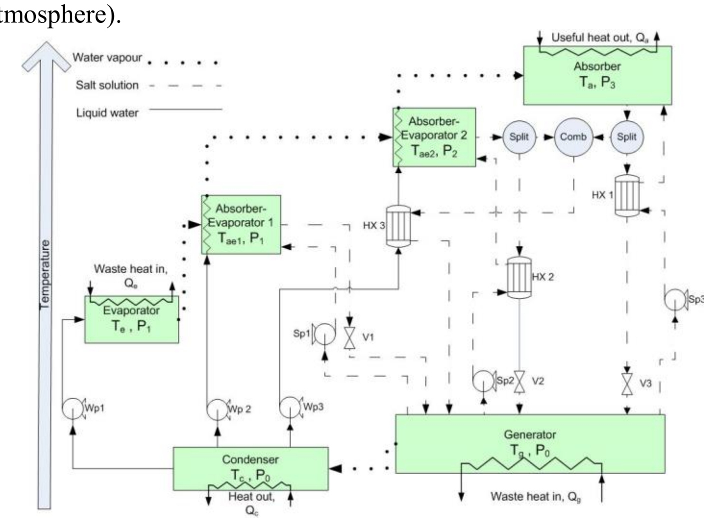

Figure 2 - Schematic of a triple absorption heat transformer (TAHT)

One fraction of the condensed refrigerant is pumped to a higher pressure (P_1) prior to entering the evaporator, where it is once more evaporated utilising an external heat source (generally the same heat source as used by the generator). This refrigerant vapour is then absorbed in absorber-evaporator-1 into the strong absorbent solution coming from the generator. Some of the heat of absorption liberated is used to maintain the absorber-evaporator-1 at a temperature higher than that of the evaporator.

The second fraction of the condensed refrigerant leaving the condenser is pumped to a pressure P_2 (greater than P_1), and is then evaporated by utilising the remaining heat of absorption being liberated by absorber-evaporator-1. This refrigerant vapour is then absorbed in absorber-evaporator-2 into the strong absorbent solution coming from the generator. Some of the heat of absorption liberated is used to maintain the absorber-evaporator-2 at a temperature higher than that of absorber-evaporator-1 (approximately 30-60˚C hotter).

The third (and final) fraction of the condensed refrigerant leaving the condenser is pumped to an even higher pressure P_3 (greater than P_2), and is then evaporated by utilising the remaining heat of absorption being liberated by absorber-evaporator-2. This refrigerant vapour is then absorbed in the absorber into the strong absorbent solution coming from the generator. Some of the heat of absorption liberated is used to maintain the absorber at a temperature higher than that of absorber-evaporator-2 (again approximately 30-60˚C hotter), while the remainder of the liberated heat energy is removed as the high temperature heat product (Q_a). The weak absorbent solutions produced in absorber-evaporator-2 and the absorber are used to preheat the respective strong solutions entering them from the generator in Hx1, Hx2 and also the condensate entering absorber-evaporator-1 in Hx3, prior to having their pressure reduced and returning to the generator.

Mathematical Modelling

Thermodynamic

The dependent factors which are being analysed in this case study are the TAHT's coefficient of performance (COP) and the total coefficient of performance of the entire installed unit (COP_{total}).

The system's COP is defined as the ratio of the useful heat product leaving the system with respect to the energy inputs into the TAHT. It can generally be regarded as the most important parameter in quantifying the thermodynamic performance of the closed cycle system and the objective is to have it at the maximum possible value.

$$COP = \frac{|Q_a|}{|Q_e| + |Q_g| + |W_{pumps}|} \tag{1}$$

The total coefficient of performance of the entire installed unit (COP_{total}) is defined as the ratio of the useful heat leaving the system with respect to the total waste heat energy contained in the heat streams.

$$COP_{total} = \frac{|Q_a|}{|Q_{WasteHeat}|} \tag{2}$$

From the above two definitions, it is clear that the total COP of the system (COP_{total}) is a function of the COP (a measure of the TAHT's internal efficiency) and of how much of the total available heat contained in the waste heat streams is extracted into the evaporator and generators (see equation 3). Generally, the reason that some of the waste heat cannot be extracted is that these streams are being cooled to temperatures lower than those of the evaporators and generators. Thus this remaining energy must be discharged to atmosphere.

$$COP_{total} = COP\left[\frac{|Q_e| + |Q_g| + |W_{pumps}|}{|Q_{WasteHeat}|}\right] \tag{3}$$

The thermodynamic modelling of the TAHT used in this case study is based upon the methods outlined in [16] and [18]. Selection of optimum operating temperatures and settings are also referenced from these studies.

Semi-empirical heat and mass transfer coefficients reported in the literature are used to model and design the individual units within the heat transformer.

Costing

The estimation of the initial capital cost of the heat transformer and the potential savings which it may generate are the most subjective aspects of this case study. The accurate costing of equipment at this stage of design is difficult to achieve based upon previous published literature or algorithms. Thus the costing of the triple absorption heat transformer is conducted instead independently by the Capital Program Manager of the oil refinery in question. This ensures that these costs are directly based upon data relating to previous purchases of similar equipment and discussions with contractors.

It has been suggested by the refinery's costing division however that the cost of equipment for this project would only represent a fraction of the overall project investment. Generally it has been found by experience that the cost of projects such as this result in a cost breakdown similar to that illustrated in Figure 3. This indicates that the cost of equipment accounts for approximately 20% of the total investment. Thus the total required project budget is estimated as five times the equipment cost. This factor is reduced to four in this case however as the system is being installed in an existing plant with electrical and piping supports already in place.

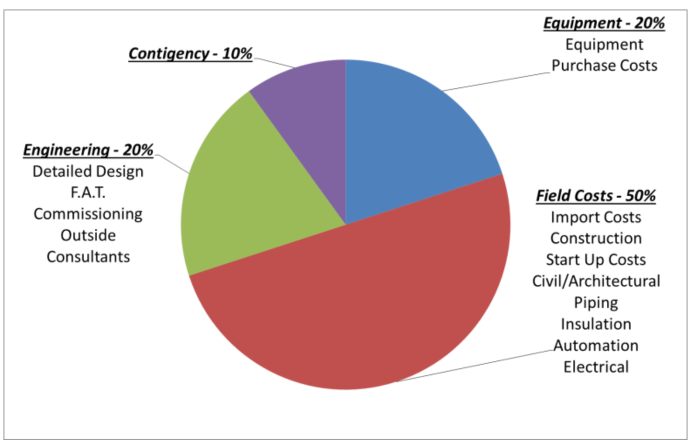

Figure 3 - Breakdown of the general trend observed for project costs in the oil refinery

The savings which may be realised by the heat transformer are strongly dependent upon the gas price which is selected. Currently (early 2014) the oil refinery estimates that their cost of gas for heating purposes is approximately \$650/tonne, and that their furnaces have an efficiency of ~80%. Taking the lower heating value (LHV) of natural gas to be 47.14MJ/kg [22], the savings achieved per annum by the TAHT is estimated by equation 4.

$$Saving = GasPrice\left[\frac{EnergyRecycled}{0.8LHV}\right] \quad (4)$$

Economic Indicators

The simple payback period (SPBP), discounted payback period (DPBP) and the net present value (NPV) are used as three simple, easily interpretable economic indicators within the paper. It should of course be emphasised that the results derived from these indicators are heavily dependent upon the price of natural gas. Thus for simplicity, the current gas price (CGP) being realised by the refinery of \$650/tonne is being used. It has been indicated by the refinery that a cost of capital of 13% is generally utilised during investment analyses, and thus a discount rate (i) of 13% is applied this investment.

The simple payback period (SPBP) is simply a ratio of the predicted annual savings generated by the TAHT to the total investment required by the project.

$$SPBP = \frac{AnnualSaving}{CapitalInvestment} \quad (5)$$

The DPBP is identical to the SPBP, except that it attempts to take into account the time value of money by including an estimated discount rate over the total project lifetime (i).

$$DPBP = \ln\left(\frac{1}{1-\left[\frac{(CapitalInvestment)(i)}{AnnualSaving}\right]}\right) \div \ln(1+i) \quad (6)$$

The net present value of an investment (equation 7) is simply an indication of the approximate net profit which will be generated by the project over the course of its lifetime (taking into account some predicted time value of money). Thus in theory, a positive net present value indicates a project which will generate sufficient revenue and should therefore be considered for investment, while in contrast a negative NPV indicates that the project is likely to result in an overall loss to the company. The project lifetime (N) is taken as 20 years in this case.

$$NPV = \sum_{y=1}^{N}\left[\frac{AnnualSaving}{(1+i)^y}\right] - CapitalInvestment \quad (7)$$

Monte Carlo Simulation

Future economic performance is by its very nature an imprecisely and unpredictable entity. However equipment and capital costs exhibit considerably less temporal variability than energy prices. Thus the potential viability of the TAHT in this study is considered using a Monte Carlo simulation on the cost of the equipment. The primary sources of inherent uncertainty in the model are the capital cost of equipment, the factorial method used to estimate the total project cost and the gas price. Based upon data gathered by the oil refinery, capital cost estimates at this stage of design may have errors of up to ±50%. Thus the projected equipment cost and the project cost factor are both taken to vary (a normal distribution is selected) with means represented by their calculated values. 99.7% of their variability is assumed to be contained within a domain of ±50% with respect to the mean (i.e.: within three standard deviations about the mean). As mentioned in the previous section, the current gas price realised by the oil refinery is being used throughout the paper.

The results of these Monte Carlo Simulations are presented in terms of probability distribution functions (PDF) and cumulative distribution functions (CDF). The CDF illustrates the probability of any result up to the current result having occurred (thus for example a CDF of 0.7 for a SPBP of 5 years indicates that there is a 70% chance of the SPBP being 5 years or less).

RESULTS AND DISCUSSION

Waste Heat Stream Physical Properties

The physical properties of the waste stream have a large influence on the economic success of failure of the heat transformer. This is identified to be mainly due to the direct influence which these waste streams have upon the size and hence costs of the evaporator and generators. To illustrate this, a simple example is used to determine the economic performance of the TAHT installed in this plant under three conditions.

1. The TAHT it is installed to just recycle the heat coming from the condensing Naphtha stream.
2. The TAHT it is installed to just recycle the heat coming from the residue oil stream undergoing a sensible heat change.
3. The TAHT it is installed to recycle the heat coming from a fictitious water stream which has the exact same mass flowrate and temperature change as in case 2 (where the residue oil line is the only waste stream).

The results of these different test cases are shown in Figures 4 to 6. From these trends it may be seen that there is a big difference between the performance of the TAHT using the residue oil (case 2) and the other two test cases. Clearly the naphtha and water heat recovery cases are much more attractive than the residue oil case.

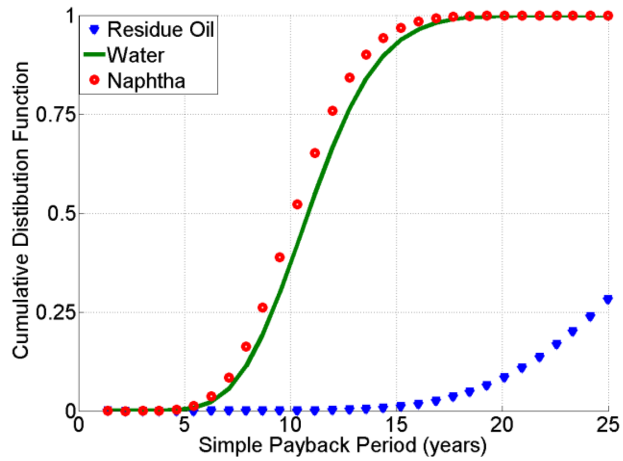

Figure 4 - Cumulative distribution function of the TAHT's simple payback period (SPBP) highlighting the importance of the waste stream's physical properties

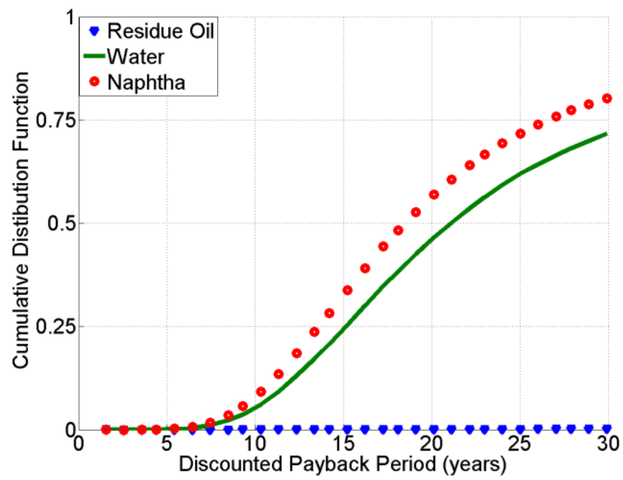

Figure 5 - Cumulative distribution function of the TAHT's discounted payback period (DPBP) highlighting the importance of the waste stream's physical properties

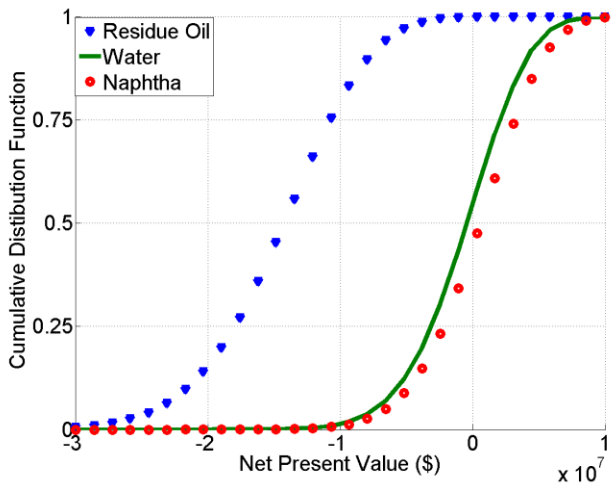

Figure 6 - Cumulative distribution function of the TAHT's net present value (NPV) highlighting the importance of the waste stream's physical properties

There are two reasons for this. The first of these is that condensing streams generally have much higher heat transfer coefficients compared to streams undergoing sensible heat changes. For example, the heat transfer coefficient for a condensing water vapour stream at 100˚C and atmospheric pressure in a vertical tube is approximately 18,000W/(m^{2}K) (assuming a vapour fraction of 0.5). In turn a liquid water stream at the same temperature and pressure (maintaining the same flowrates and tube conditions) has a heat transfer coefficient of ~1,025W/(m^{2}K). In the heat transformer's evaporator, the waste heat stream is being cooled by the evaporation of pure water. The evaporation of water (using the same tube conditions once more) also has a very high heat transfer coefficient of approximately 20,000W/(m^{2}K). Due to this large evaporating heat transfer coefficient, the resistance to heat transfer is primarily due to the waste heat stream (assuming the resistance of the metal wall is negligibly small). Thus if a condensing stream is used, then it is clear that a smaller heat transfer area will be required per unit of heat energy transferred.

The second reason is the difference in physical properties of the waste heat fluid. In general, Nusselt number correlations are functions of the flow's Reynolds and Prandtl number. The Dittus-Boelter equation for turbulent single phase pipe flow is shown as an example in equation 8. The same equation is then rewritten in terms of its basic components and the heat transfer coefficient in equation 9.

$$Nu = 0.023\,\mathrm{Re}^{4/5}\,\mathrm{Pr}^{0.3} \tag{8}$$

$$\alpha = 0.023\left[\frac{\rho^{0.8} c_p^{\,0.3} k^{0.7}}{\mu^{0.5}}\right]\cdot\left[\frac{v^{0.8}}{D^{0.2}}\right] \tag{9}$$

From equation 9 it can be seen that for efficient sensible heat exchanges with a waste stream, the stream should ideally have a high density, specific heat capacity and thermal conductivity while maintaining a low viscosity. As the condensing heat transfer coefficient correlation developed by Shah [23] utilises equation 9 as a base (equation 9 is then modified by a function based upon the vapour fraction), this general principle may also (cautiously) be applied to condensing waste heat streams (the physical properties then refer the fluid's liquid phase).

The residue oil stream being utilised in this industrial case study satisfies none of the above physical property criteria. It is very viscous. For example, at 90˚C, its viscosity is more than 80 times that of water at the same temperature. In contrast however, its thermal conductivity is 7 times less than water's while its specific heat capacity and density are also lower. The result of this is that unacceptably low heat transfer rates are obtained in both the evaporator and generator serving it.

The Naphtha stream being condensed also has relatively poor physical properties compared to water (although not as bad as the residue oil). However it still has a slightly superior economic performance (Figures 4 to 6) which highlights the ability of a latent heat change to compensate for a stream's poor physical properties. A comparison between the water and residue oil sensible heat change cases illustrates clearly however that for two streams which are alike (i.e.: two condensing streams or two streams undergoing sensible heat changes) the physical properties are vital. Water's superior physical properties mean that a positive net present value may be achieved (under the assumptions made during this analysis with respect to maintaining the current gas price) while in turn the probability of making any return on the initial investment is almost zero if the residue oil stream is being utilised on its own.

TAHT using available heat streams

In the previous section, the economic performance of the TAHT is used to compare the suitability of different waste heat streams. In the current industrial case study however, it wished to recycle both available waste heat streams, namely the Naphtha and residue oil lines. The economic performance of the TAHT recycling the energy from these two streams simultaneously is therefore discussed in this section.

Thermodynamically, the unit achieves a COP of 0.21, which corresponds to a COP_{total} of 0.14. This implies that 14% of all the waste heat energy available can be recycled by the TAHT. The total purchase cost of equipment is estimated to be ~$6.8million. Thus using the oil refinery's factor method, the total project investment is approximated at ~$27million.

It should be noted that two evaporators and two generators are being used. This allows one evaporator and generator pair to cool the residue oil, and the other evaporator and generator pair to cool the naphtha.

Figures 7 to 9 illustrate the economic performance of this TAHT, and it is clear that it does not appear to be financially viable under these conditions. In order for an energy project such as this to merit consideration in the oil refinery in question, payback periods of less than 3-5 years must be projected. Thus the mean predicted simple payback period of ~11 years does not satisfy these criteria. In addition, Figure 9 also predicts that there is almost no chance that the investment will generate the required return on investment over its entire lifetime of 20 years to ensure a positive NPV.

In addition to the poor return on investment, the probability distributions exhibit a degree of unfavourable skewness. Figure 7 and in particular Figure 8 illustrate that the probability density functions are weighted to the right, and thus if a payback period were to be quoted in terms of a plus or minus figure, the negative confidence interval (a favourable outcome) would have to be less than the positive confidence interval (an unfavourable outcome).

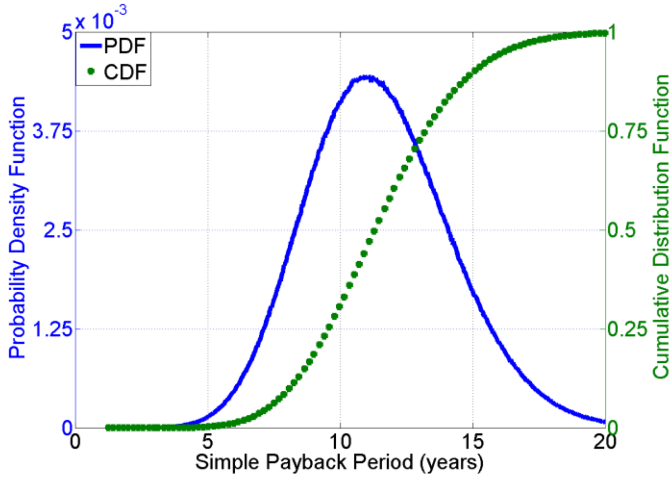

Figure 7 - Cumulative distribution function of the TAHT's simple payback period (SPBP) based upon the current gas price (CGP)

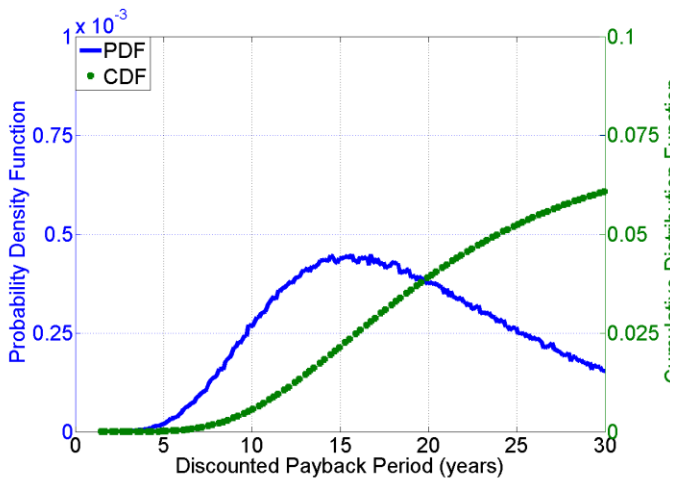

Figure 8 - Cumulative distribution function of the TAHT's discounted payback period (DPBP) based upon the current gas price (CGP)

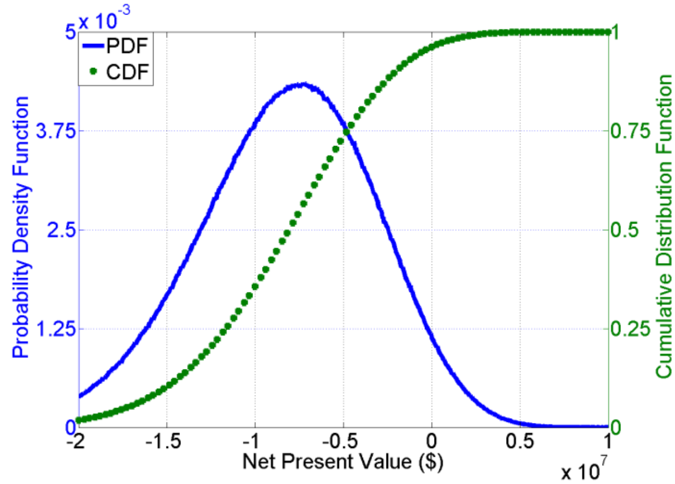

Figure 9 - Cumulative distribution function of the TAHT's net present value (NPV) at the end of its project lifetime based upon the current gas price (CGP)

Applicability in different Plants

In the currently examined oil refinery, two waste heat streams are available, namely one viscous oil line which is undergoing a sensible heat change, and a condensing stream. It has been demonstrated previously in this paper that the oil stream is extremely unsuitable for use in such a system due to its unfavourable physical properties. In Figures 7 to 9 it is demonstrated that even with the presence of condensing Naphtha stream the TAHT is not economically viable at current gas prices. In this section however, it will be tested whether this unattractiveness is also due in part to the quantity of waste heat being made available.

In Figures 10 to 12 the results of using different waste heat streams at different flowrates in the TAHT are presented. Six different scenarios are tested, namely the use of the current two streams (as discussed in the previous section), the residue oil line at two different flowrates (on its own), and three different flowrates of condensing Naphtha (on its own). The three different Naphtha flowrates are taken as the current flowrate (called Naphtha), doubled the current flowrate (2xNaphtha) and four times the current flowrate (4xNaphtha). Similarly the two different Residue oil flowrates are taken as the current residue flowrate (called Res Oil) and doubled the current flowrate (2xRes Oil).

It may be seen that utilising the residue oil waste heat stream in this case study in fact decreases the economic performance of the heat transformer compared to just using the currently available Naphtha stream on its own. It is quite clear however that increasing the quantity of condensing waste heat energy being recycled dramatically increases the attractiveness of the technology. If the quantity of the current condensing Naphtha stream were to be increased by a factor of four, then the probability of having a simple payback period of less than seven years increases from approximately 7% to almost 100%, and the mean payback period expected is ~5 years. In contrast, doubling the mass flowrate of Residue oil generally decreases the performance of the TAHT (especially apparent in Figure 12) highlighting once more the importance of selecting streams with appropriate physical properties discussed earlier.

It can be seen from Figures 10 to 12 that an increase in the amount of waste heat available to the TAHT increases the economic performance of the unit as long as suitable fluids are selected. This is due to the fact that the price of heat exchangers does not rise linearly with size, but generally begins to plateau at larger dimensions. The savings availed of due to the recycled energy does increase linearly however, and thus by increasing the waste heat energy available for recycling, the savings being made by the heat transformer grow faster than the size of the required investment. If the quantity of Naphtha being condensed increases by a factor of two or four, it may be seen from Figure 12 that a positive NPV is predicted in almost every scenario analysed. Thus this is a strong indicator that triple stage heat transformers are highly influenced by scale, and that they are most suited to large energy intensive operations. The oil refinery being analysed is a small oil refinery, with a crude oil throughput of approximately 70,000 barrels/day. In the worldwide oil refining industry, this represents a relatively small figure, with some of the largest refining plants having a throughput of between 500,000-1,200,000 barrels/day. Thus the result demonstrated in this section that the economic viability of the TAHT increases rapidly with an increase in the waste heat energy available means that such a system, while excessively expensive in this small refinery at current gas prices, would be well suited to larger plants.

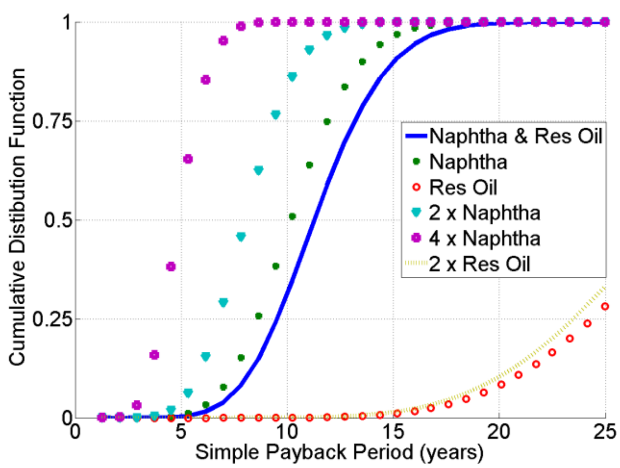

Figure 10 - Cumulative distribution function of the TAHT's simple payback period (SPBP) utilising different waste heat streams in the TAHT

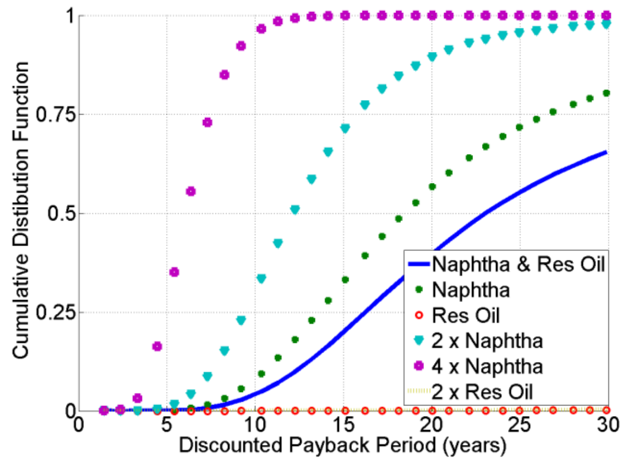

Figure 11 - Cumulative distribution function of the TAHT's discounted payback period (DPBP) utilising different waste heat streams in the TAHT

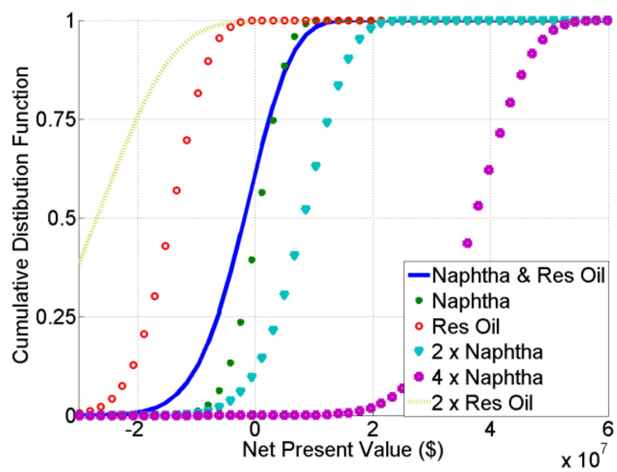

Figure 12 - Cumulative distribution function of the TAHT's net present value (NPV) utilising different waste heat streams in the TAHT

CONCLUSIONS

An industrial case study has been conducted which examines the economic viability of installing a triple absorption heat transformer in a small oil refinery. Analysis indicates that the type of waste heat stream utilised in such a system is vital to the success of failure of the investment. The examined plant has two available heat sources, namely a viscous residue oil line and a condensing naphtha stream. The unfavourable physical properties of the residue oil mean that any equipment which it comes in contact with must be excessively large and which implies that payback periods may be longer. The available condensing stream is capable of a dramatically improved economic performance. The use of this condensing stream alone is however not capable of achieving a financially attractive return on investment, as payback periods of approximately 10 years are predicted. It is demonstrated that this problem may be overcome if the quantity of condensing energy is increased. By increasing the amount of energy available for recycling by a factor of two or four, a positive return on investment is predicted in almost all examined scenarios. Thus it may be concluded that at the current low gas price, the use of a triple stage absorption heat transformer is mainly suited to larger plants with sufficient waste energy available for recycling.

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