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Estimation of Maximum Available Heat Using Different Temperature Driving Forces by a Mathematical Surface Technique

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Abstract

A lot of re-usable thermal energy within industrial processes is emitted into the environment every year in the world as energy waste. The aim of this paper was to study the estimating of maximal available heat flow rate using different temperature driving forces by a mathematical surface technique. This technique is based on the usage of pinch analysis principles. The maximal available heat flow rate with different temperature driving forces can be calculated by using a trapezoid surface area within a grand composite curve. This technique can be applied by upgrading large quantities of available heat for steam or electricity generation within industrial processes. The research idea, which is presented using a mathematical surface technique, is founded on increasing the available heat flow rate with different temperature driving forces by using the excess and available heat flow rates regarding waste streams. This technique was tested on an existing formaldehyde process that allows for efficient and additional steam production of 1.2% with a higher outlet temperature for steam generation.

Keywords: Available heat flow rate; Waste heat; Mathematical method; Temperature; Steam

Introduction

The European Union has set climate targets for the reduction of greenhouse gas (GHG) emissions, as well as for an increased share of renewable energy and reduced use of primary energy. GHG emissions are targeted for a reduction of 20% by 2020, relative to 1990 levels [1], and 20% of the total share of the energy used in the EU should originate from renewable sources. Also, the use of primary energy should be reduced by 20%, based on a projected level for 2005, coming through energy efficiency measures [2]. The Energy Efficiency Directive establishes a framework of measures that promote energy efficiency and the directive identifies recovery of industrial excess heat as one way to attain the EU target [3].

To improve the environmental performance of biofuel production by exploiting various opportunities for synergy have been discovered [4]. Such collaboration can take different forms: by-product synergies allow for the use of by-products generated during a production process and utility synergies involve sharing energy (e.g. excess heat use).

About 35% of the input energy is being lost through the waste heat streams [5]. Replacing diesel fuel with waste heat recovery from kiln and cooler exhaust for the drying of raw meal and fuel, and preheating of combustion air, a cement industry can save about 1.264×10^5 US dollars per year [6]. Waste heat recovery to a cement plant for increasing the energy efficiency of the plant. Cogeneration of power besides mitigating the problem of power shortage helps in energy conservation as well as reducing green-house gas emissions [7].

Brown [8] presented waste heat can be reused for some useful technical and economic purposes. Determining a strategy for recovering this heat depends on the temperature of the waste heat gases and the economics involved.

The chemical and petrochemical sector is hitherto the largest industrial energy user, accounting for 30% of the industry's total final energy use [9]. The electricity, steam and by-products of some plants account for the required energy regarding the processes. Steam has the largest share because the energy that it supplies is involved in many processes. Various energy sources, such as natural gas, fuel oil, and liquid petroleum gas are used in producing steam and its heating process has two different heat temperature values: low heating (42°C) and medium heating (141°C).

A lot of usable thermal energy from industrial processes is emitted into the environment every year in the world as energy waste causing and serious thermal pollution. The absorption heat transformer (AHT) could be applied for upgrading the large quantity of low-grade waste heat with temperatures of 60-100°C in industrial processes [10,11].

Recovery of the waste heat within condensate and reuse of the water may provide avenues for decreasing net energy and water use at processing facilities. However, new processing methods are needed for creating demand for the condensate waste heat [12,13].

Rowe stated that the use of waste heat at temperatures below 140°C as an energy source could be a competitive method for generating electricity [14]. Waste heat is normally produced by machinery, electrical equipment and industrial heat-generating processes. In the process industry, waste heat can be classified into high, medium, and low temperature ranges. The high temperature range is above 650°C, medium temperature is between 230°C and 650°C, and low temperature is below 230°C [15]. The operations of process industries are inefficient and emit large quantities of waste heat. Approximately 33% of total consumed energy has been ejected into the surroundings because of inability to recycle the excess energy [16].

Pinch analysis, along with other principles of process integration, has established itself as one of the more important tools for analysing and optimising the energy systems of process plants. The principles of

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pinch analysis were formulated by Linnhoff et al. as presented in their book [17]. The second edition as presented in 1994 [18], included heat exchanger networks (HEN) synthesis, heat recovery targeting and selecting multiple utilities. The second edition [18] was elaborated on by Kemp [19] in a book that includes optimisation of energy use, and energy saving using practical applications. Forty years of heat integration by using pinch analysis and mathematical programming has been described by Klemeš and Kravanja [20].

Shenoy presented energy optimisation methodologies based on pinch analysis and mathematical programming for the synthesis of optimal heat exchanger networks [21]. These methodologies involve three-steps: targeting, network synthesis, and detailed design. They have been used for identifying energy savings in grassroots designs,

Wang and Smith researched the minimisation of wastewater within process industries [22]. Targets are first set that maximise water re-use. The approach used allows individual process constraints relating to minimum mass transfer driving force, fouling, corrosion limitations, etc.

Waste reduction through source reduction and on-site recycling is an important aspect of pollution prevention [23]. Techniques of process integration may be used for pollution prevention. In this paper an algorithmic procedure is presented for reducing waste generation through maximising on-site reuse/recycling. The proposed methodology is based on pinch principles and establishes a minimum waste generation target prior to detailed network design.

Heat integration is a key tool for energy saving achieved by heat recovery within process industries [24]. Energy saving plays an important role in achieving sustainable future development. Heat recovery at the Total Site level can provide a considerable potential for energy saving, as presented in [25].

A simple exergetic model for estimating cogenerational potential for a total site based on the site source and the site sink profiles. Based on the total site source and sink profiles. Site utility composite curves for given steam levels. A temperature-enthalpy (T–H) model based on Salisbury approximation and on the observation that the specific power produced by the turbine is approximately proportional to the differences in saturation temperatures. A site utility grand composite curve has been presented for providing designers with a tool for determining the potential for cogeneration.

If available heat from different processes is integrated within another process this can reduce energy usage. Hui and Ahmad introduced the potential for transferring energy between processes by a common steam system that yielded near-minimum cost designs. Steam generated in one process can be used in others. This provides indirect heat transfer between processes.

Methods for reducing energy have been developed for several years. These methods are supplemented for use within industry and include multi-criteria optimisation, steam generation, and wastewater collection for steam generation. The energy saving was effective on the lower CO_2 emissions. The utility can be save within internal or between processes including the estimating of maximal energy recovery. This paper currently presents the estimating of maximal available heat flow rate with different temperature driving forces using a mathematical surface technique.

Mathematical Surface Technique

The re-usage of waste can reduce carbon emissions and the usages of fossil fuels within industrial processes. The goal of the surface technique is to estimate the maximal available heat flow rate using different temperature driving forces. Estimated analysis includes the waste and outlet flow rate within the process. This technique is very useful regarding energy recovery without changing the basic process operation and the reusing of flow rate and reducing the energy loss. This technique includes the modifications of cogeneration plants by generating additional steam using waste heat recovery, therefore it is a more economic option. The possibility of recovering the waste flow rate as steam using a waste heat boiler has been investigated or generating electricity.

This technique presents estimating of the maximal availability of waste heat flow rate within industrial regions. Consequently, by implementing a smart heat recovery system to convert the waste heat flow rates into useful energy can help achieve industrial cost saving.

Over recent years, engineers and scientists have directed their attention to waste heat flow rate recovery for cheaper energy generation. Waste energy recovery techniques can also be useful for increasing the efficiencies of conventional energy conversion systems.

The surface technique, as a simple method of energy modification using different temperature driving forces, is based on heat flow rate saving targets using pinch analysis and/or mixed integer nonlinear programming (MINLP) algorithms. Pinch analysis is a methodology for minimising the energy consumptions of chemical processes by calculating thermodynamically-feasible energy targets and achieving them by optimising heat recovery systems, energy supply methods, and process operating conditions.

The surface would include only those streams that are available for heat flow rate, therefore this would not change the basic operations.

This surface technique is based on the usage of the grand composite curve (GCC) including the process, waste, and outlet streams (Figure 1). The different supposed steam generation lines (S= 1… S_{max}) are placed under the GCC. The estimating of maximal available heat flow rate with different temperature driving forces ($A_{MH,S}$ in WK) by a mathematical surface technique can be calculated by using a rotated trapezoid surface area under the grand composite curve (eq. 1):

$$A_{MH,S} = [(b_{1,S} + b_{2,S})h_S]/2 \quad S=1\ldots S_{max} \qquad (1)$$

Where,

$b_{1,S}$=base 1 for different supposed steam generation line

$b_{2,S}$=base 2 for different supposed steam generation line

h_S=height for different supposed steam generation line

The height (h_S) presents the maximal heat flow rate (in W) of different steam generations. The maximal available heat flow rate with different temperature driving forces ($A_{MH,S}$ in WK) presents more efficient steam production with different outlet temperatures of steam generation. Higher value of $A_{MH,S}$ presents steam generation with higher temperature driving forces. Smaller value of $A_{MH,S}$ presents the steam generation with lower temperature driving forces until the limit steam generation ($A_{MH,L}$):

$$A_{MH,L} = [(b_1 + b_2)h]/2 \qquad (2)$$

Where,

b_1=10 K

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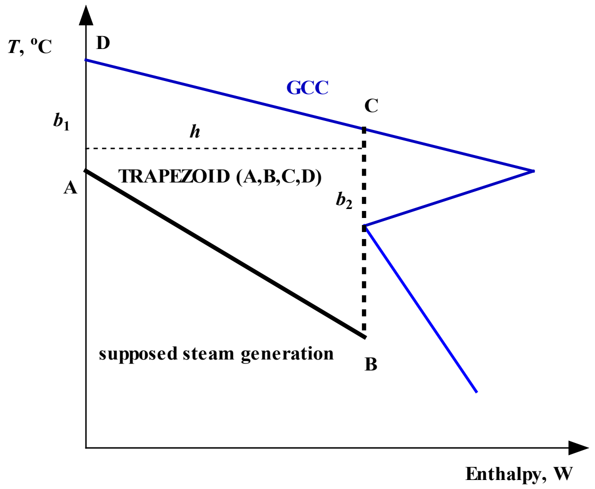

Figure 1: A flow diagram of the maximal available heat flow rate with different temperature driving forces estimation.

b_2=10 K

h=height

The different supposed steam generation lines can be placed under the GCC that can be selected by using the mixed integer nonlinear programming (MINLP) algorithms.

The selection between different supposed steam generation lines can be denoted by discrete (or binary) variables *SS*(S) that are selected by only one or none:

$$\sum_{s} SS(\mathrm{s}) \leq 1 \quad \mathrm{S}=1\ldots \mathrm{S}_{max} \tag{3}$$

The objective function (OBF, Eq. 4) of the MINLP model maximised for additional profit. The additional income would be accounted for the additional production of steam (In(S) during the steam production. The basic additional cost of steam production would be the cost of additional modifications (C(S)).

$$OBF = \sum_{s} (SS(S)\cdot h_S \cdot In(S) - SS(S)\cdot h_S \cdot C(S)) \quad \mathrm{S}=1\ldots \mathrm{S}_{max} \tag{4}$$

Many constrained engineering and industrial optimisation problems can be modelled as mixed integer nonlinear programming (MINLP) problems. The MINLP approach deals simultaneously with both continuous and discrete (as binary) variables. Whilst continuous variables are defined for the continuous optimisation of parameters (heat flow rate-*h*), discrete 0–1 variables are used to express discrete decisions, i.e., usually the existence (1) or non-existence (0) of structural elements within the defined structure. As the discrete optimisations are carried out simultaneously, together with continuous optimisation, the MINLP approach additionally determines the optimal continuous parameters. The handling of binary (y = 0, 1) variables allows for the specifications of those constraints that are relevant for synthesising the practical flow-sheet structure, in our case selection between different steam generations.

In addition the binary variables can be related to activating or deactivating continuous variables, inequalities or equations: As an example, consider the conditions for the continuous variable *x*, in our case the heat flow rate:

if y=1 → L ≤ x ≤ U, if y=0 → L x=0,

which can be modelled through the constraint: $Low\cdot y \leq x \leq Up\cdot y$

Where *Low (L)* is the lowest value and *Up* is the highest value of the parameters.

Case Study

The surface technique is a very simple method that was tested during oxide formaldehyde production. Formaldehyde is an important chemical used widely by industry for manufacturing building materials and numerous household products. Its primary use is during the production of resins and as a chemical intermediate. Urea-formaldehyde and phenol formaldehyde resins are used in foam insulations, as adhesives during the production of particle board and plywood, and in the treatment of textiles.

Although formaldehyde is a gas at room temperature, it is readily soluble in water and is more commonly sold as a 37% solution in water known by trade-names such as formalin or formol.

Formaldehyde is produced industrially by the catalytic oxidation of methanol. The more common catalysts are silver metal or a mixture of an iron oxide with molybdenum and vanadium. During the more commonly used FORMOX® process, methanol and oxygen react at ca 252-400°C in the presence of iron oxide in combination with molybdenum and/or vanadium to produce formaldehyde according to the chemical equation:

$$2\,CH_3OH + O_2 \rightarrow 2\,H_2CO + 2\,H_2O \tag{R1}$$

Another possibility for formaldehyde production is the metal oxide process. The main differences compared to the silver process are:

- working with excess air
- type of catalyst
- a lower temperature level

The metal oxide process can be described as a two stage oxidation reaction during the vaporisation phase, which involves an oxidised (Kox) and a reduced (Kredox) catalyst.

Methanol (inlet stream M) is fed into the heated vaporiser (V; Figure 2). The process gas, a mixture of fresh air (inlet stream air) from the atmosphere, is drawn through a filter and compressed in a blower (B). The methanol and air mixture are heated in a vaporiser (V) and pre-heater (H) before entering the reactor (R). The conversion of methanol to formaldehyde takes place in tubes filled with a metal oxide catalyst. The reaction's heat is removed by using steam production or for electricity cogeneration. The reactive gases are cooled (C) and enter the absorption tower (A), where the absorption of the formaldehyde takes place by using 5,478 kg/h (1.52 kg/s) of fresh water. The exiting low-pressure steam production (S=3) take places for 7,000 kW with outlet temperature of 110°C by using heat flow rate within an exothermic reactor and cooler C (Figure 2).

Mathematical surface technique using oxide formalin production

The grand composite curve (GCC) includes the process and outlet streams (Table 1 and Figure 3). The different supposed steam generation lines (S=1, 2, 3) are placed under GCC. The estimating of maximal available heat flow rates with different temperature driving forces for supposed steam generation lines S=1, S=2 and S=3 ($A_{MH,1}$, $A_{MH,2}$ and $A_{MH,3}$) were calculated by using a rotated trapezoid surface area under

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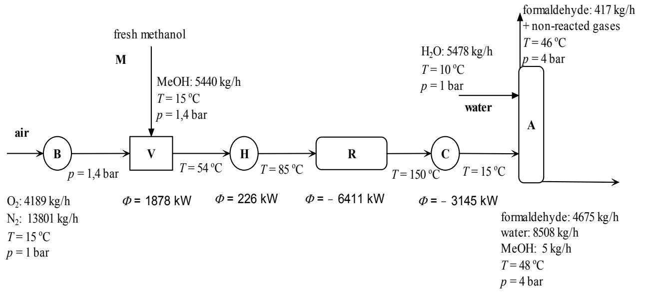

Figure 2: Simple oxide formaldehyde production process.

Stream	T_s/°C	T_t/°C	I/kW
C+C-1process hot	150	15	3130
Rprocess hot	300	150	6500
Aprocess hot	48	47	1740
V+Hprocess cold	6	85	2100
Productoutlet streams	48	40	94
S=1Steam generation 1	80	120	/
S=2Steam generation 2	90	130	/
S=3Existing steam gen.	80	110	/

Table 1: Process and outlet streams, and steam generation streams of the existing oxide formalin process.

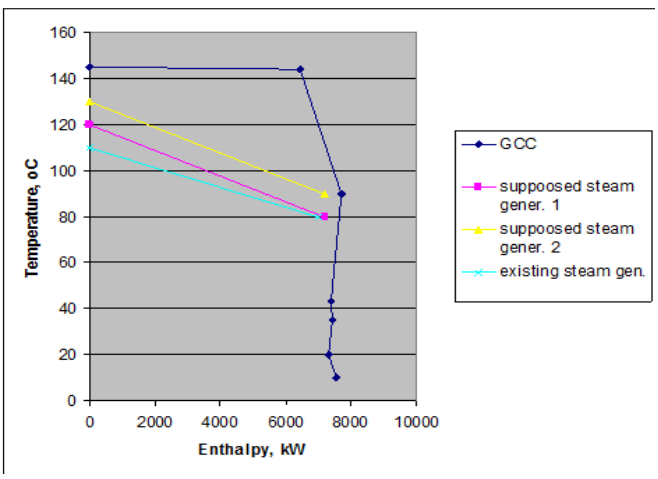

Figure 3: A flow diagram of the maximal available heat flow rate with different temperature driving forces estimation for oxide formalin production.

the grand composite curve by using equation 1 (Figure 3 and Table 1):

$$A_{MH,1} = [(b_{1,1} + b_{2,1})h_1]/2 = [(25 + 65)7,300]/2 = 328,500 kWK \quad (5)$$

$$A_{MH,2} = [(b_{1,2} + b_{2,2})h_2]/2 = [(15 + 55)7,300]/2 = 255,500 kWK \quad (6)$$

$$A_{MH,3} = [(b_{1,3} + b_{2,3})h_3]/2 = [(35 + 65)7,000]/2 = 350,000 kWK \quad (7)$$

The maximal heat flow rates (h_1 and h_2) for both steam generations S=1 and S=2 were 7,300 kW. The maximal heat flow rate for existing steam generation S=3 was 7,000 kW. The maximal available heat flow rate for supposed steam generation line S=1 presented the higher temperature driving force and lower outlet temperature of steam generation. The maximal available heat flow rate for supposed steam generation line S=2 presented the lower temperature driving force and higher outlet temperature of steam generation. The limit steam generation ($A_{MH,L}$) was 73,000kW:

Steam production	C(S), EUR/kWa	In(S), EUR/kWa
S=1	30	60
S=2	40	80
S=3	0	50

Table 2: Additional cost and the additional saving of different steam production.

$$A_{MH,L} = [(10 + 10)7,300]/2 = 73,000 kW \quad (8)$$

S=1, S=2 and S=3 supposed steam generation lines were placed under the GCC by using mixed integer nonlinear programming (MINLP) algorithms and equations 3–4 (Table 2):

$$\sum_s SS(s) \le 1 \quad S=1, 2, 3 \quad (9)$$

The objective function (Eq. 4) was adapted for retrofit (OBF, Eq. 10) including the existing steam production (h_{ex}=7,000 kW).

$$OBF = \sum_s [SS(S) \cdot (h_S - h_{ex}) \cdot In(S) - SS(S) \cdot (h_S - h_{ex}) \cdot C(S)] \quad S=1, 2, 3 \quad (10)$$

The MINLP selected the steam generation of S=2. 12,000 EUR/a of the additional maximal profit can be obtained by a higher heat flow rate of 300 kW and outlet temperature (130°C) of generation steam. The modification of existing steam generation does not require a major changes that need additional demineralised water.

Conclusion

The re-usage of waste heat has positive effects on the amount of resources and waste and pollutants generated within industries. Waste-heat recovery techniques that are environmentally friendly and have technical and economic advantages should be assessed for possible contributions to the energy economy and national economy.

The mathematical surface technique, as a simple method of steam generation modification, is based on more efficient steam generation targets, using pinch analysis and/or MINLP. The benefit of this technique is more optimal steam generation streams by using the waste and heat flow rate of the outlet stream. The surface technique, as a simple method, for estimating of the maximal available heat with different temperature driving forces. The maximal available heat flow rate with different temperature driving forces can be calculated by using a trapezoid surface area under the grand composite curve. This method can be selected between the different supposed steam generation lines. Modified existing formaldehyde process allows for 300 kW higher heat flow rate of steam generation and with higher outlet temperature of steam generation. The outcome from the presented research confirms the importance of more efficient steam generation.

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