Total Site Targeting Approach for Heat Recovery at a Paper Factory

JUAN PEDRO HERNÁNDEZ TOUSET[1,a], JOSÉ ULIVIS ESPINOSA MARTÍNEZ[2,b]
[1]Departamento de Ingeniería Química,
Universidad Central Marta Abreu de Las Villas,
Alemán 120 y San Cristóbal, Santa Clara,
CUBA

[2]Departamento de Ingeniería Industrial,
Universidad Central Marta Abreu de Las Villas,
Carretera a Camajuani, km 5.5, Santa Clara
CUBA

[a]ORCiD: https://orcid.org/0000-0002-0032-8685
[b]ORCiD: https://orcid.org/0000-0003-0558-7843

Abstract: - The total Site heat integration approach has been used extensively in the industry, including process services and heat exchanger network design integrated with the site service system. This work aims to propose a design for the heat recovery network in the paper factory through Total Site targeting. A procedure that includes the energy analysis and Pinch Analysis methodologies, with the use of Aspen Energy Analyzer is applied. The heat exchanger network design through total site heat integration shows that the rehabilitation of the heat recovery system of the paper machine and boiler blowdown is feasible, with a potential annual saving of 259 t of fuel oil and 116 000 m^3 of water, which make it feasible to invest in the factory's heat recovery system, whose project budget is estimated to recover in a year. Heat exchanger network retrofit design allows to recover 46.2% of the maximum energy recovery.

Key-Words: - heat integration, total site, paper mill, energy analysis, blowdown, drying.

Received: May 14, 2023. Revised: October 15, 2023. Accepted: December 6, 2023. Published: December 31, 2023.

1 Introduction

Thermal energy recovery represents a key aspect of the sustainable design and operation of processing plants, as minimizing energy consumption translates into reduced environmental impacts and costs. Heat recovery in an industrial process takes place through the heat recovery system, a set of units where the exchange of thermal energy between two or more mediums occurs, [1]. Instead improved energy efficiency should be aiming at increased mechanical dewatering in the press section and increased waste heat recovery from the exhaust moist air, [2]. During industry operations, large portion of the energy input is dissipated as waste heat to the ambient in different forms, resulting in severe energy waste. Recovering such waste heat can provide power, heat or cooling output without extra energy input. This increases the energy utilizing efficiency and is considered to be a significant "technology wedge" with the potential to contribute a particular figure for the emission reduction, [3].

Thermal drying is often responsible for more than 80% of the total steam use. The paper machine drying section and its operating principles have remained almost unchanged since their initial development; contact drying with steam-heated cylinders is still the dominant method for drying paper and board, [4]. To decrease energy costs different forms of heat recovery are applied to energy-dense flows, such as exhaust air from paper machines, where excess energy may be transferred into secondary energy such as warm water which may be utilized for low or partial heating of incoming flows. Due to several improvements and reconstruction of equipment, the heat recovery systems may be operating far from their original design, and opportunities for improvement might exist. In a typical paper machine, 60 % of energy may be expected to be recovered in heat recovery, while the rest is exhausted outside, [5].

A large amount of heat energy is required at the drying section of a paper factory for the removal of the large quantity of water present in the paper web by evaporation. The majority of the heat then would be available as latent heat of vaporization. The means of recovery of the waste heat and its cost-effectiveness can only be established if one can quantify the amount of the heat with an acceptable degree of accuracy, [6].

In paper drying thermal conductivity is a fundamental property that has a determining influence on the temperature distribution and heat flux density during thermal heating, [7], and convective heat transfer must meet the requirements in terms of improving thermal performance and energy efficiency, [8].

The goal of Pinch Analysis (PA) is to maximize energy recovery in industrial processes to reduce their need for external energy sources. In this method, all streams are categorized into either hot or cold streams. The pinch analysis aims to provide the required energy of cold streams by the hot streams. One of the most important goals of PA is to minimize the total annual cost of the plant without negatively affecting the thermodynamic performance of the system. To do so, the total area of heat exchangers should be minimized, [9]. For optimal heat transfer, it is sufficient to know all the streams involved, without needing to make a priori assumptions about how they will be connected.

PA has been successfully used in a great number of industrial applications. Limitations of the method have motivated the search for more efficient mathematical techniques for handling HEN optimization problems, where genetic algorithms have been used for synthesizing a process including HEN, [10]

The PA tool has been extended to consider energy integration across several plants or processes using indirect heat transfer, termed Total Site (TS) heat integration, [11].

Total Site Profile (TSP) analysis can identify the opportunities for Inter-Process Integration via the utility system and the preparation of the appropriate integration strategy, [12].

Potentials for heat recovery have not been properly identified in the paper mill, which affects the energy performance indicators. This work aims to propose a design for the heat recovery network in the paper mill through TS targeting.

2 Methodology

Energy management in the paper manufacturing process is based on the Cuban standard ISO 50001: 2019 and a methodology for energy usage, [13]. By applying energy analysis and Heat Integration, energy performance indicators (EnPIs) are determined. Pinch Analysis methodology is applied to determine network targets, minimum temperature difference, and maximum energy recovery (MER), [14]. Data processing was performed by Aspen Energy Analyzer, [15].

3 Results and Discussion

3.1 Energy Usage Analysis in the Paper Factory

The paper factory produces kraft paper, cardboard, and liner from old corrugated containers (OCC). The steam utility consists of one water-tube boiler with a superheated steam generation capacity of 20 t/h at 2.5 MPa and 398 º C, which consumes Fuel Oil. The steam pressure for the process is 0.054 – 0.5 MPa. The dryer section is enclosed by a semi-open hood, where the top half of the cylinders is covered with an insulated hood but not covered at the bottom of the cylinders.

Figure 1 shows the paper factory steam network diagram**.**

Mass and energy balances are applied for the production of 3,965 kg/h of liner with a basic weight of 200 g/m2 and a paper machine speed of 90 m/min. Table 1 shows the results of the steam, heat, and water balances in the factory and the heat balance in the drying section, [16]. The result of the boiler blowdown calculation is added.

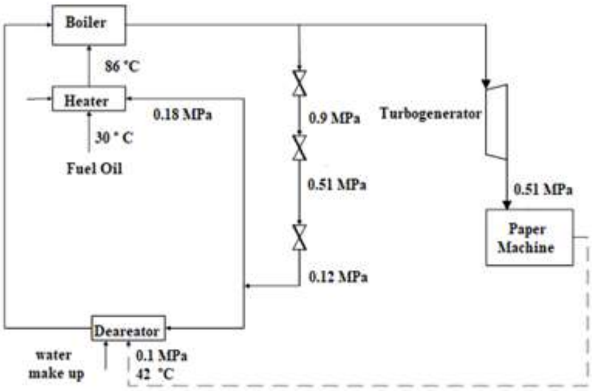

Fig. 1: Paper factory steam network diagram.

Energy balance provides vegetable vapor flow and boiler blowdown, which constitute essential streams for the application of the Pinch Analysis Method.

Table 1. Energy usage analysis

Parameter	Value
Heating duty, kW	8,871
Steam consumption, kg/h	15,134
Heat losses , kW	3,016
Drying section thermal efficiency, %	66.0
Vegetable vapor, kg/h	8,172
Sensible heat from vegetable vapor, kW	456.0
Latent heat from vegetable vapor, kW	5,239
Boiler blowdown, kg/h	2,857
Condensate, kg/h	817.0
Water make up, kg/h	6,912
Fuel oil consumption, kg/h	740.0
Specific steam consumption, t / t paper	3.8

3.2 Heat Recovery Network Analysis and Design

Figure 2 shows the process flowsheet and stream data is presented in Table 2. The streams considered in the analysis are: Vegetable vapor (H1); Cylinder condensate (C1); Wet paper streams (C2 – C31); Boiler blowdown (H2); Feed water (C32); Fuel (C33); film coefficients for hot and cold utilities are 5,000W/m^2°C and 3,000W/m^2°C, [17]. Process equipment are boiler (2), and dryers (1). There are 41 cylinders; in 10 cylinders there is a temperature drop in the paper sheet at the exit of the cylinder, caused by a temperature decrease of the steam in the cylinder; therefore, they are not taken into account as cold streams, since they are hot currents that cool without receiving external cooling service, which introduces an error in the application of Pinch Analysis Method.

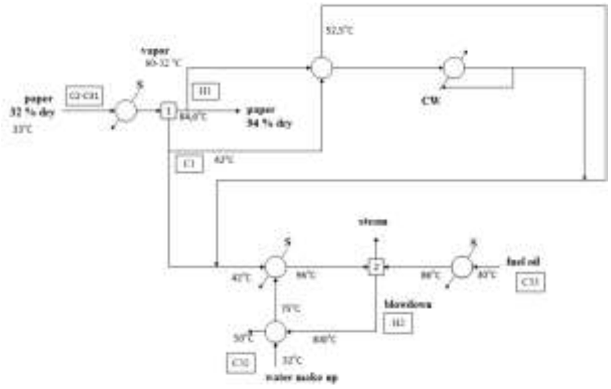

Fig. 2: Process flowsheet

Nomenclature: cp = specific heat capacity (kJ/kg °C), Tf= final temperature (°C), Ti= initial temperature, m = flowrate (kg/h), CP = heat capacity flowrate (kW/ ° C), h = film heat transfer coefficient (kW/m^2 ° C), ΔH = heat load (kJ/h). Steam properties are calculated for 0.4 MPa.

The global minimum temperature difference (ΔT$_{min}$) in this case is set at 20 °C, because is de minimum temperature difference between process streams. There is one Pinch point, at 52 ° C, with a hot and cold pinch at 62 ° C and 42 ° C. The minimum hot and cold duties are 1,653,000 kJ/h and 931,200 kJ/h. The Composite Curves in Figure 3 show the minimum hot and cold duties. There is an energy potential (MER) of 3,810,606.64 kJ/h, feasible to be recovered.

Table 2. Streams data

Stream	Ti (°C)	Tf (°C)	m (kg/h)	cp (kJ/kg°C)	CP=m·cp (kJ/h°C)	ΔH (kJ/h)	h (kJ/m²°C)
H1	80	32	8,172	4.19	34,240.68	1,643,552.64	10,800
C1	42	90	15,134	4.19	63,352.8	3,040,934.4	10,800
C2	33	37	4,212	1.3	5,475.6	21,902.4	3,600
C3	37	50	4,212	1.3	5,475.6	71,182.8	3,600
C4	48	58	4,212	1.3	5,475.6	54,756	3,600
C5	58	63	4,212	1.3	5,475.6	27,378	3,600
C6	62	63	4,212	1.3	5,475.6	5,475.6	3,600
C7	70	72	4,212	1.3	5,475.6	10,951.2	3,600
C8	71	76	4,212	1.3	5,475.6	27,378	3,600
C9	76	76.3	4,212	1.3	5,475.6	1,642.68	3,600
C10	76	80	4,212	1.3	5,475.6	21,902.4	3,600
C11	80	82	4,212	1.3	5,475.6	10,951.2	3,600
C12	81	82	4,212	1.3	5,475.6	5,475.6	3,600
C13	82	83	4,212	1.3	5,475.6	5,475.6	3,600
C14	82	83	4,212	1.3	5,475.6	5475,6	3,600
C15	60.7	79.7	4,212	1.3	5,475.6	104036,4	3,600
C16	79	95	4,212	1.3	5,475.6	87609,6	3,600
C17	94.6	96	4,212	1.3	5,475.6	7665,84	3,600
C18	92	93	4,212	1.3	5,475.6	5475,6	3,600
C19	72.6	79.1	4,212	1.3	5,475.6	35,591.4	3,600
C20	70	79.7	4,212	1.3	5,475.6	53,113.32	3,600
C21	67.7	92.5	4,212	1.3	5,475.6	135,794.88	3,600
C22	72	82	4,212	1.3	5,475.6	54,756	3,600
C23	78	95	4,212	1.3	5,475.6	93,085.2	3,600
C24	60	63	4,212	1.3	5,475.6	16,426.8	3,600
C25	62.8	78.3	4,212	1.3	5475.6	3,943,527.12	3,600
C26	76	77.2	4,212	1.3	5,475.6	6,570.72	3,600
C27	60.4	64.3	4,212	1.3	5,475.6	21,354.84	3,600
C28	64	67	4,212	1.3	5,475.6	16,426.8	3,600
C29	57	64	4,212	1.3	5,475.6	38,329.2	3,600
C30	63,3	63.4	4,212	1.3	5,475.6	547.6	3,600
C31	63.2	72.9	4,212	1.3	5,475.6	53,113.32	3,600
C32	32	75	6,912	4.19	28,961.28	1,245,335	720.0
H2	300	40	2,844	4.19	11,916.36	3,098,254	720.0
C33	30	86	770.0	2.09	1,609.3	90,120.8	720.0

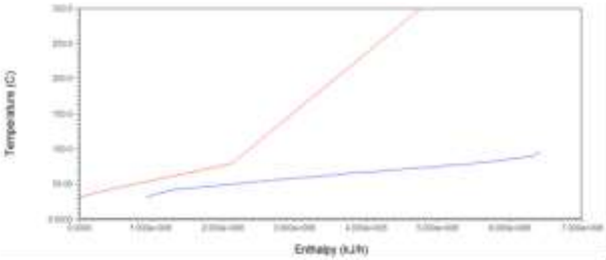

Fig. 3: Composite curves diagram

Figure 4 and Figure 5 show the location of the heat exchangers in the feasible combinations. According to the algorithms for stream splits, [17]; above the pinch, the number of hot streams (N$_h$) has to be less than the number of cold streams (N$_c$) and it is verified that CPh ≤ CPc (above pinch), that is, 34,240. 68 kJ/h°C<63,352.8 kJ/h°C, therefore, the combination of streams H1 and C1 (heat exchanger E101) is feasible. The second possible exchange occurs between streams H2 and C32, which comply with the CP inequality rule (E102). Below the pinch, there are no feasible combinations.

Table 3 presents the heat exchanger data as a result of HEN design.

Table 3. Heat Exchangers data

Equipment	Cold stream	Ti ºC	Tf ºC	Hot stream	Ti ºC	Tf ºC	Load kJ/h	Area m^2	ΔT min cold ºC
E-101	C1	42	52.5	H1	81.5	62	665,9	5.43	20
E-102	C32	42	75	H2	142.2	62	955,7	44.1	20
Sum							1,621,6		

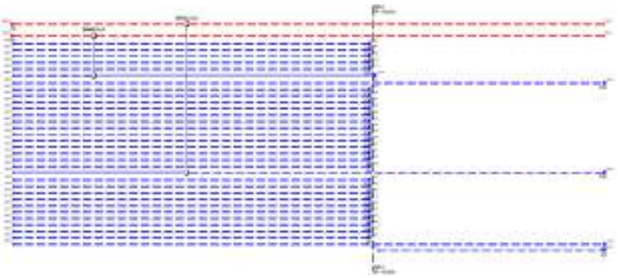

Fig. 4: HEN design

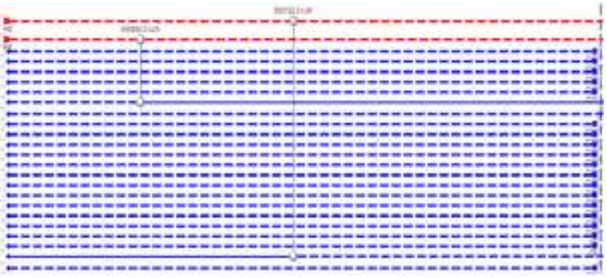

Fig. 5: HEN above Pinch

Table 4 shows hot and cold utility duties from energy analysis, minimum hot and cold utilities, energy recovery, and the energy and financial resources potential savings of the heat recovery system in the paper mill. A net caloric value of the fuel of 43,157 kJ/kg, 300 days of operation per year, 20 hours/day, and fuel (FO) and water prices of \$512.9 /t and 0.1 \$/m^3 are assumed. Potential savings to estimate the feasibility of investment projects are based on the energy recovered. In the heat exchange between the vegetable steam and the condensate from the cylinders, the temperature of the boiler condensate is raised by 12.5 º C. In the heat exchange between the purge condensate stream and the make-up water, the temperature rises from 42 º C to 75 º C. Through the two exchanges, annual savings of 259 t of fuel and 115,776 m^3 of cooling water are achieved. For the purposes of estimating the investment cost, fuel and cooling water savings are considered. The cold utility is saved in the exchange between process streams by using 7.78 m^3/h of condensed vegetable steam that is recovered and recirculated for condensation and cooling vegetable steam stream. In the boiler heat recovery system, savings in hot utility are achieved by combining the boiler blowdown stream with water make-up. The modified Total Site heat recovery network design allows to recover 46.2% of the maximum energy recovery. This methodology is feasible to be applied in processes where vapor stream waste heat can be used. It was recently applied in a raw sugar refinery with significant fuel and water savings, which motivates the continuity of research in this field, [18].

Table 4. Fuel and water savings

Duty	Energy analysis		Heat Integration ΔTmin = 20ºC				Savings		
	kW	t/h	Mínimum utility kW	m³/h	t/h	Recovered energy kW	t/y	m³/y	\$/y
Hot (steam)	8871	15,13	459	-	0,8	450	259	-	110,8
Cold (water)	-	-	259	11,13	-	450	-	115,776	11,6
Sum									122,4

4 Conclusion

The design of the heat recovery system through Total Site heat integration shows that the rehabilitation of the heat recovery system of the paper machine and the steam generator is feasible, with a potential annual saving of 259 t of fuel oil and 115,776 m^3 of water. There is a high excess of current hot utility duty about the minimum hot duty, a behavior that is associated with the data extraction system. Total Site Heat exchanger network retrofit allows 46.2 % of the maximum recoverable energy to be recovered. Fuel and water savings make it feasible to invest in the heat recovery system. This study allows us to continue the research to rehabilitate hot air system to the hood.

References:

[1] Vocciante, M., Kenig E.Y., Pillow-Plate Heat Exchangers: an Overview on Advances, Limitations and Prospects, *Chemical Engineering Transactions*, Vol.88, 2021, pp. 865-870.

[2] Stenström, S., Drying of paper: A review 2000–2018, *Drying Technology*, Vol. 38, No.7, 2020, pp.825-845.

[3] Xu, Z. Y., Wang, R.Z., Yang, C., Perspectives for low-temperature waste heat recovery, *Energy*, Vol. 176, 1 June, 2019, pp. 1037-1043.

[4] Jankes, G., Tanasic, N., Stamenic, M., Adžic, V., Waste Heat Potentials in the Drying Section of the Paper Machine in Umka Cardboard Mill, *Thermal Science*, Vol. 15, No. 3, 2011, pp. 735-747

[5] Öhman, T., Improvement of heat recovery in the paper industry, Master's Thesis, Department of Chemical Engineering, Faculty of Science and Engineering, Åbo Akademi University, 2018, pp. 1-63, [Online]. https://www.doria.fi/bitstream/handle/10024/165142/ohman_tommy.pdf?sequence=2&isAllowed=y (Accessed Date: February 23, 2024).

[6] Yisahak, M., Dribssa, E., Didwania, M. A Methodology for Determination of Waste Heat and Water Recovery Potential from the Dryer Section of a Pulp and Paper Factory. *International Journal of Scientific & Engineering Research*. Vol. 8, No. 5, 2017, pp. 1552-1557.

[7] Umbricht, G., Rubio, D., Tarzia, D., Determination of Thermal Conductivities in Multilayer Materials, *WSEAS Transactions on Heat and Mass Transfer*, Vol. 17, 2022, pp. 188-195, https://doi.org/10.37394/232012.2022.17.20.

[8] Khaoula Ben Abdelmlek, Fayçal Ben Nejma, Energy Efficiency Analysis of Natural Convection Heat Transfer in Concentric Annulus with Interior and Exterior Grooves, *WSEAS Transactions on Heat and Mass Transfer*, Vol. 18, 2023, pp. 99-118, https://doi.org/10.37394/232012.2023.18.10.

[9] Moosazadeh, S.A., Mafi, M., Kaabi, A., Salehi, G., Torabi, M., A new method to boost the performance of heat recovery steam generators by integrating pinch and exergy analyses, *Advances in Mechanical Engineering*, Vol. 10 No.5, 2018, pp.1–13.

[10] Dipama, J., Teyssedou, A., Sorin, M, Synthesis of heat exchanger networks using genetic algorithms, *Applied Thermal Engineering*, Vol. 28, 2008, pp. 1763–1773.

[11] Liew P.Y., Wan Alwi S.R., Klemes J.J., Varbanov P.S., Manan Z.A., Total site heat integration with seasonal energy availability, *Chemical Engineering Transactions*, Vol. 35, 2013, pp. 19-24.

[12] Grip, C., Isaksson, J., Harvey, S., Nilsson, L., Application of Pinch Analysis in an Integrated Steel Plant in Northern Sweden, *SIJ International*, Vol. 53, No.7, 2013, pp. 1202–1210.

[13] Hernández, J.P., de Armas, A.C., Espinosa, R., Pérez, O., Guerra, L., Energy analysis procedure for the conversion of sugar cane industries into biorefineries (Procedimiento de análisis energético para la conversión de industrias de la caña de azúcar en biorrefinerías), *Revista Universidad y Sociedad*, Vol. 13 No.5, 2021, pp. 277-288.

[14] Klemeš, J. J. (Ed), *Handbook of Process Integration(PI): Minimisation of Energy and Water Use, Waste and Emissions*, Woodhead Publishing Limited, Cambridge, 2013.

[15] Aspentech, Aspen Energy Analyzer V 10. Aspen Technology Inc., 2017, [Online]. https://www.aspentech.com/en/products/engineering/aspen-energy-analyzer (Accessed Date: February 24, 2024).

[16] Hernández, J. P., García, A., Rodríguez, L., Assessing opportunities for energy conservation in a paper machine (Evaluación de oportunidades para la conservación de la energía en una máquina de papel, *Revista Tecnología Química*, Vol. 41, No. 1, 2021, pp. 174-192, [Online]. https://tecnologiaquimica.uo.edu.cu/index.php/tq/article/view/5187/4657 (Accessed Date: February 23, 2024).

[17] Smith R. (Ed), *Chemical Process Design and Integration*, John Wiley & Sons, Ltd., Chichester, West Sussex, 2016,

[18] Hernández, J., Peralta, L., Hernández, L., Energy performance and heat recovery assessment in a sugar refinery (Evaluación del desempeño energético y la recuperación del calor en una refinería de azúcar), *Revista Cubana de Ingeniería*, Vol. XIII (3) e337, 2022, pp. 1-11, [Online]. https://rci.cujae.edu.cu/index.php/rci/article/view/848 (Accessed Date: February 23, 2024).

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Juan Pedro Hernández Touset was responsible for research methodology.
- José Ulivis Espinosa Martínez was responsible for data extraction.

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.