Energy 57 (2013) 565–573

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

An assessment of a pulp and paper mill through energy and exergy analyses

Zafer Utlu [a,*], Olcay Kincay [b]

[a] İstanbul Aydin University, Engineering and Architecture Faculty, Mechanical Engineering Department, TR 34455 Florya, Istanbul, Turkey
[b] Yildiz Technical University, Mechanical Engineering Faculty, Mechanical Engineering Department, TR 34349 Besiktas, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 22 November 2012
Received in revised form
25 May 2013
Accepted 28 May 2013
Available online 25 June 2013

Keywords:
Energy
Exergy
Pulp and paper mill
Recycled waste paper

ABSTRACT

In this study, a pulp and paper mill (PPM) in the SEKA Papermaking Plant in İzmit, Turkey, is analysed through energy and exergy balances. The plant utilises recycled waste paper for papermaking. This type of raw material input makes the process highly sophisticated. The pulping uses strictly mechanical processes, such as digestion, separation by screening and hydrocyclone, and refining. The milling, as an integrated process, provides the final operations necessary to prepare the conditions required for the end-product by stock-preparation, wiring, rolling, and drying by dewatering, pressing, and evaporation. The possibility of making the entire process more thermodynamically efficient is discussed by calculating the energy and exergy losses for all the mechanical and physical sub-processes. The study shows that the energy efficiencies for each of the mechanical and physical steps in the PPM vary between 34% and 97.4%, whereas the exergy efficiencies vary between 30.2% and 94.2%. In conclusion, based on the results from the energy and exergy flow analyses, the exergy output can be improved through more efforts directed primarily to further measurements toward more efficient energy utilisation in the PPM.

1. Introduction

Recent studies have started to focus on how to capture some of the energy that is currently lost in pulp and papermaking processes and on identifying possible areas with energy-saving potential that could also provide a deeper and true insight into a variety of different industries. Pulp and papermaking operations have a high demand for energy, which accounts for approximately 50% of the operational costs. The greatest energy-saving potential in the pulp and paper industry lies in improving energy distribution and equipment efficiency. Therefore, it is very important to analyse the energy flows as a base case to direct more efficient energy utilisation in the pulp and paper industry, especially when processing waste paper [1].

The amount of paper and paper products wasted by households is a major problem in many countries due to relatively small landfill capacities. This situation is a strong argument for different recycling and trade rates for waste paper being relatively different for every country. Van Beukering and Bouman [2] report that paper recycling and trade patterns are caused by geographic and economic conditions and the international trade flow of recyclable materials between developed and developing countries. Developed countries that have actively participated in the trade of recyclables have higher recycling rates than do developing countries with closed recycling systems that import waste materials recovered from developed countries. In contrast to the approach by Van Beukering and Bouman, Berglund and Söderholm [3] criticise the regression analysis of the waste paper utilisation rates and argue that an increased focus on relative waste paper availability provides a better understanding of global paper recycling. Other studies indicate that the utilisation and recycling patterns of waste paper is a market-driven issue and is dependent on long-term macro-economic conditions [4]. The attractiveness of recycling waste from paper mill operations is increasing due to pressures to develop new landfill management methods as a result of a lack of landfill capacity, forthcoming waste disposal and landfill management legislation and the use of non-renewable and energy-intensive natural resources for the end-treatment of old landfills [5,6].

In an integrated pulp and paper mill, drying is the most energy-intensive step, and improvements to the exergy efficiency are difficult to implement. Because the energy supply is a critical factor in determining cost across industries, recent studies have focused mainly on how to minimise the plant energy cost by implementing

* Corresponding author.
E-mail addresses: zaferutlu@aydin.edu.tr, zafer_utlu@yahoo.com (Z. Utlu), okincay@yildiz.edu.tr (O. Kincay).

0360-5442/$ – see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.05.054

numerous designs and processes to increase the energy and exergy efficiencies [7–12].

An exergy analysis is a useful tool to simultaneously associate engineering systems with the surrounding environment. It can be applied to any industrial process to establish energy flows and determine exergy losses to increase the true efficiency of an engineering system [13–15]. An energy balance is the first step to examine how efficiently energy is utilised in a process before establishing an exergy balance. The results obtained from energy and exergy analyses can be used for benchmarking between current processing conditions and those derived by other technologies. From these results, priorities such as the energy consumption rate and the efficiency of every operation can be easily determined. Unlike energy, which only is concerned with the quantity, exergy as an efficient thermodynamic tool for energy policymaking applications is a measure of both the quantity and the quality of the energy sources. The role of exergy is discussed from several key perspectives, e.g., quality, energy conservation, the environment, the economy, and sustainable development [13,16]. The potential usefulness of an exergy analysis for examining environmental problems indicates that there are three main relations between exergy and environmental impact, which are, destruction, resource degradation and waste exergy emissions. The interactive relationship between thermodynamics and the environment, and exergy and the environment are based on the first and the second laws of thermodynamics. Exergetic and energetic analyses can determine the magnitude of the imperfections in a process by providing a comprehensive and convenient approach to outlining the steps required to improve the operational system characteristics [4,13]. Szargut et al. [12], Kotas [17] and Wall [18] have performed extensive studies in the field of exergy. Szargut et al. studied cumulative exergy consumption and the cumulative degree of perfection for industrial processes. Kotas examined different processes, such as sulphuric acid production, gas turbines and refrigeration plants, whereas Wall established exergy flows for every process step in pulp and paper mills and steel plants. Several studies related to energy flow analyses have specifically focused on the pulp and paper industry. However, exergetic studies focusing on the papermaking process utilising recycled paper have still not been reported in the literature [1–12,19–25].

In this study, a pulp and paper mill in the SEKA Pulp and Paper Mill (PPM) in İzmit, Turkey, is analysed by examining possibilities for making the entire operation thermodynamically efficient and analysing all mechanical and physical sub-processes for energy and exergy losses.

2. Theoretical analysis

In this section, the basic thermodynamic concepts derived for a steady-state/steady-flow process are briefly introduced. The balance equations given in Section 2.1 are used to determine the work and heat interactions, the rate of decrease in exergy, the rate of irreversibility, and the efficiencies of energy and exergy [17,18,25–31].

2.1. Mass, energy and exergy balances

The mass balance for a steady-state/steady-flow thermal process can be expressed as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}. \tag{1}$$

The general energy balance is given as

$$\sum \dot{E}_{in} = \sum \dot{E}_{out}, \tag{2}$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out}, \tag{3}$$

$$\dot{Q} = \dot{Q}_{net,in} = \dot{Q}_{in} - \dot{Q}_{out},$$

where $\dot{Q}$ is the rate of net heat input, $\dot{W} = \dot{W}_{net,out} = \dot{W}_{out} - \dot{W}_{in}$ is the rate of network output, and h is the specific enthalpy.

The energy balance given in eqaution (3) can be expressed in terms of enthalpy and mass flow rate:

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out}. \tag{4}$$

The general exergy balance in rate form can be expressed as either

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{5}$$

or as

$$\sum \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W} + \sum \dot{m}_{in}\psi_{in} - \sum \dot{m}_{out}\psi_{out} = \dot{E}x_{dest}, \tag{6}$$

$$\psi = (h - h_0) - T_0(s - s_0), \tag{7}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k and location k, $\dot{W}$ is the thermodynamic work, ψ is the flow exergy, s is the specific entropy, and the subscript zero indicates that the properties are in the dead state P_0 and T_0.

The exergy destruction, or irreversibility, may be expressed as

$$\dot{I} = \dot{E}x_{dest} = T_0 \dot{S}_{gen}, \tag{8}$$

where $\dot{S}_{gen}$ is the entropy generation rate. The amount of thermal exergy transfer associated with the heat transfer Q_r across a system boundary r at a constant temperature T_r is given in references [32–35] and is shown here as

$$ex^{Q} = [1 - (T_0/T_r)]Q_r. \tag{9}$$

The exergy of an incompressible substance may be written as

$$ex_{ic} = c\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right), \tag{10}$$

where c is the specific heat.

2.2. Exergy of a flowing stream

Consider a flowing stream at temperature T, pressure P, chemical composition μ_j mass m, specific enthalpy h, specific entropy s, and mass fraction x_j of species j.

For a conceptual environment in an equilibrium state with intensive properties of T_0, P_0 and μj_{00}, the environment must be large enough that the intensive properties are negligibly affected by any interactions with the system. From these considerations, the specific exergy of the flowing stream can be expressed as [31]

$$\Psi = [ke + pe + (h - h_0) - T_0(s - s_0)] + \left[\sum_j \left(\mu_{j0} - \mu_{j00}\right) xj\right] \tag{11}$$

Note that the above equation can be separated into physical and chemical components (assuming $ke = 0$ and $pe = 0$). The physical exergy $[(h - h_0) - T_0(s - s_0)]$ is the maximum available work capable of being extracted from a flowing stream as it is brought to the state of the surrounding environment. The chemical exergy

$[\sum_j(\mu_{j0}-\mu_{j00})xj]$ Chemical exergy is the maximum amount of work obtainable when a substance is brought to the chemical equilibrium with the environment (or true dead state) at constant temperature and pressure. Comparing this definition with a similar definition for the exergy of a stream of substance show that chemical exergy is the exergy of a stream of substance when the state of the substance corresponds to the environmental state [17]

2.3. The reference environment

Exergy is always evaluated with respect to a reference environment. The equilibrium reference environment acts as an infinite system, is a sink or a source for heat and materials, and experiences only internally reversible processes in which the intensive properties (temperature T_0, pressure P_0, and chemical potentials μ_{j00} for each j component) remain constant. With minor exceptions, Gaggioli and Petit's model [32] is used to define a reference environment in which $T_0 = 10\ ^\circ C$, $P_0 = 1$ atm, the chemical composition is considered to be air saturated with water vapour, and the following condensed phases are used at 25 °C and 1 atm: water (H_2O), gypsum ($CaSO_4$, $2H_2O$), and limestone ($CaCO_3$). According to Gaggioli and Petit [32], gypsum and limestone are considered part of the reference environment to provide nonreactive, dead state chemical forms for materials such as sulphide and calcium. Generally speaking, limestone ($CaCO_3$)is soft rock whose surface can be scratched easily and fine-grained. Its hardness ranges from 3 to 4 on Moh's scale, and its density varies from 2.5 to 2.7 kg/cm^3. Its compressive strength is 1800–2100 kg/cm^2. And it has less than 1% water absorption. Waste powder limestone ($CaCO_3$) from paper industries was used in the limestone neutralization stage of the process. Chemical composition of powder limestone ($CaCO_3$); $CaCO_3$ (97.02%), $Ca(OH)_2$ (3.87%), Ca (354.08 mg/g), Mg (5.56 mg/g), Na (11.17 mg/g), K (0.43 mg/g), moisture (24%).

The chemical composition of gypsum is $CaSO_4 \cdot 2H_2O$. The mineral is composed of 55.76 percent oxygen, 23.28 percent calcium, 18.62 percent sulfur and 2.34 percent hydrogen.

2.4. Energy and exergy efficiencies

Different ways of formulating the exergetic efficiency have been proposed in the literature [31–33]. The exergy efficiency expresses all exergy input as used exergy, and all exergy output as utilised exergy. Therefore, the exergy efficiency ε_1 becomes

$$\varepsilon_1 = \frac{\dot{E}x_{out}}{\dot{E}x_{in}}. \tag{12}$$

There is often some part of the output exergy that is unused, i.e., wasted exergy or $\dot{E}x_{waste}$ to the environment [34].

The rational efficiency is defined by Kotas and Cornelissen [17,33] as the ratio of the desired exergy output to the exergy used:

$$\varepsilon_2 = \frac{\dot{E}x_{desired,output}}{\dot{E}x_{used}}, \tag{13}$$

where $\dot{E}x_{desired,output}$ is the total exergy transfer rate from the system, which must be regarded as constituting the desired output plus any by-product that is produced by the system, whereas $\dot{E}x_{used}$ is the required exergy input rate for the process to be performed.

The exergy efficiency defined in equation (13) may also be expressed as [35]

$$\varepsilon_3 = \frac{\text{Desired exergetic effect}}{\text{Exergy used to drive the process}} = \frac{\text{Product}}{\text{Fuel}}. \tag{14}$$

To define the exergetic efficiency, both the *product* and the *fuel* for the system being analysed are identified. The product represents the desired result of the system (power, steam, some combination of power and steam, etc.). Accordingly, the definition of the product must be consistent with the purpose of purchasing and using the system. The fuel represents the resources expended to generate the product and is not necessarily restricted to being an actual fuel such as a natural gas, oil or coal. Both the product and the fuel are expressed in terms of exergy [35].

The energy and exergy utilisation efficiencies in terms of percentages, η and ε_1, can be respectively defined as

$$\eta = [(\text{Energy in products / Total energy input})]*100, \tag{15}$$

$$\varepsilon_1 = [(\text{Exergy in products/Total exergy input})]*100. \tag{16}$$

2.5. Improvement potential

Van Gool [36] has noted that the maximum improvement in the exergy efficiency for a process or system is achieved when the exergy loss or irreversibility $(\dot{E}x_{in} - \dot{E}x_{out})$ is minimised. Consequently, Van Gool suggests that it is useful to employ the concept of an exergetic "*improvement potential*" when analysing different processes or sectors of the economy [37] and defines this in rate form, denoted as IP:

$$\dot{I}P = (1-\varepsilon)\left(\dot{E}x_{in} - \dot{E}x_{out}\right). \tag{17}$$

3. Description of the pulp and paper mill process and its energy use

The energy consumption of a pulp and paper mill depends on the raw materials used, the type of pulping process and the degree and type of final products [38]. Papermaking as a sophisticated process can be divided into major sub-operations, as illustrated in Figs. 1 and 2. This integrated process incorporates an integrated mill (pulp and paper mills) with a paper mill. In an integrated mill, there are different operational sections called zones, such as processing, power and utilities. A pulp mill is divided into a series of sub-operations such as cooking, pulp washing, bleaching, washing and sheet forming, whereas a paper mill performs stock preparation, approaching, head-box, wire-forming, pressing, drying, sizing and winding.

Pulping, in which the raw inputs are either chemically cooked or mechanically ground, is the most energy-intensive operation. This process makes the papermaking industry the fourth most energy-intensive sector in the world [22–24]. Depending on the grade of paper and the technology used, an amount of heat energy equivalent to 5–17 GJ is needed to produce one tonne of paper. This demand for energy is higher than that of other energy-intensive sectors such as cement and steel production. Therefore, there are significant savings potentials in the pulp and paper industry for which fossil fuels and electricity are still the major non-renewable energy inputs [25].

Pulping and paper finishing are the most important process steps, and they determine the final grade of the paper produced. The average specific energy consumption from the pulping process is low in industrialised countries because of the higher percentage of waste-paper pulp used. The specific energy consumption of waste-paper pulp is approximately three times less than that of wood pulp [38]. Pulp can be produced by mechanical or chemical processes. Mechanical pulping uses the heat generated by means of rotating equipment to soften and mechanically separate the fibres,

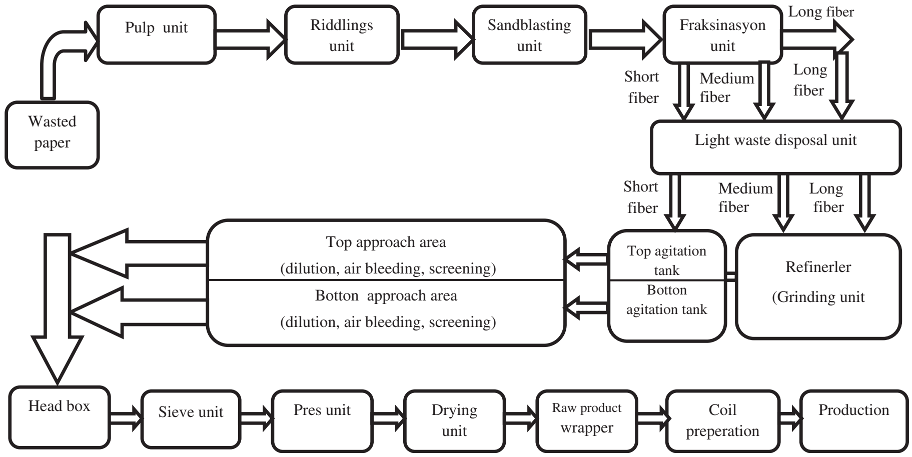
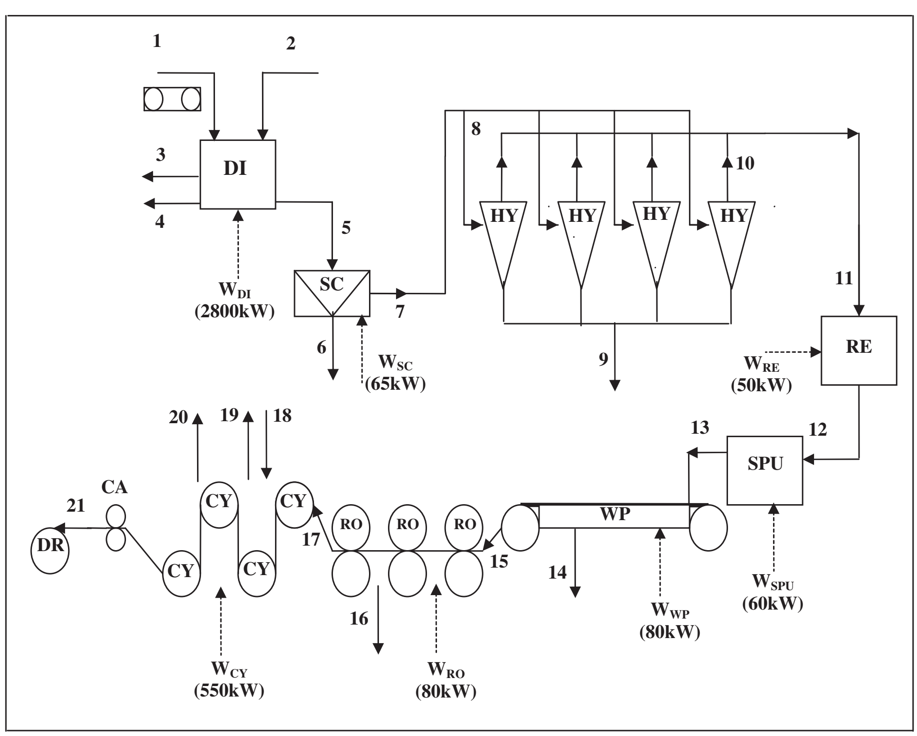


Fig. 1. Material flow and process chain for the paper production.

whereas chemical pulping cooks the chips with chemicals at a specified pressure. Mechanical and chemical pulping processes have typical specific energy consumption patterns. Under normal operating conditions, a modern chemical pulp mill provides for at least half of its energy requirements by chemical recovery. However, the process electricity required for mechanical pulping is significantly higher than that required for chemical pulping. Much of the higher energy input is likely attributable to the wood species employed and the grade of paper produced [39].

The energy requirements of a pulp and paper mill can be met by energy conservation measures to reduce the energy use and to recover energy from the internal waste fuels. A 10% increase in the amount of recycled paper used can lead to an energy savings of approximately 6.5% for the pulping process. Additionally, the amount of chemicals recovered has a positive effect on the overall specific energy consumption of the pulp and paper industry. The expected level of waste paper in the papermaking process has grown significantly and in parallel with both the increase in demand and the increase in prices in the markets. Developing countries tend to use a smaller percentage of waste paper input compared to developed countries. The use of waste paper as a raw material for paper production is being emphasised due to increasing energy costs and global competitiveness [22,38].

The SEKA PPM located in İzmit, Turkey, is used here as a reference site in order to examine exergy reduction opportunities in its sulphide-cellulose preparation plant, which cooks the chips with an acid sulphite solution at a high temperatures. The typical specific yearly energy consumption rate for the SEKA Plant is an amount



DI; Digester , SC: Screen, HY: Hydrocyclone , RE: Refiner, WP: Wire Part, RO: Roller, SPU: Stock Preparation Unit, CY: Steam-Heated Cylinder,

Fig. 2. Common steps of the pulp and paper mill production processes.

equivalent of 3122.5 TJ of fuel oil and 564.6 TJ of electricity. The SEKA Cellulose and Paper Factory have three major manufacturing lines. The first produces quality white paper, newsprint paper and board. The last two lines can utilise recycled or waste paper in the papermaking. The pulp and paper mill studied here has a production capacity of 90 tonnes a day of grey and pink board from 100 tonnes of recycled waste paper, as illustrated in Fig. 2. The process for the selected pulp and paper mill can be outlined as follows:

- Recycled waste paper and water are fed and mixed in a continuous digester (DI);
- The pulp and liquor removed from the DI are screened (SC);
- The screened pulp is washed in hydrocyclone separators (HY), refined in a refiner (RE) and pumped to the stock preparation unit (SPU);
- The stock is dried along the paper mill by dewatering in the wiring portion (WP), pressed through three rollers (RO) and has the water removed via evaporation by means of forty steam-heated cylinders (CY);
- The dried board is passed between the rolls (DR) of a calendaring apparatus (CA);
- Finally, the boards, with remarkably improved smoothness and gloss, are sorted for the delivery.

The sulphide – cellulose preparation plant has three subsections: sulphide-cellulose solvent production, boiling, and bleaching. The plant receives energy in the form of heat from two sources: the central boiler, operating at a pressure of 1176.8 kPa, and the waste heat recovery boiler operating at 2550 kPa, and regulated down to 540 kPa through a local throttle valve. In this study only the boiling solvent line was considered, as illustrated in Fig. 2. Sulphur dioxide is produced by burning pyrite in a fluidised bed of combustion cells. The calcium bisulphate used as the boiling solvent is obtained by reacting sulphur dioxide with calcium carbonate and water in a packed bed tower.

4. Results and discussion

In this study, energy and exergy recovery opportunities were examined to improve the exergy efficiency of the PPM system installed in the SEKA Plant in İzmit, Turkey. The data were obtained both from the selected system and from the literature. The effects of flow velocities were neglected except for the data given in Table 1. To perform a thermodynamic analysis of the PPM, the following assumptions were made:

4.1. Process steps in exergetic assessment for pulp and paper mills units

The methodology used consists of the following steps in the process analyses

- The first step is to establish the system boundaries by drawing a flow diagram of the industrial process under study, determining which inputs/outputs stages and by-products are part of the system.
- In defining system boundaries, factors such as fuel and energy carriers, trace inputs/outputs and pre-treatment stages must be taken into account before drawing a process flow diagram.
- The process is broken down into operation units to study each one independently. An operation unit is defined as a unit of the process with a set of working conditions specific to the reaction such as evaporation, separation and acidulation.
- The working conditions defined for each operation unit are the residence time, pressure, temperature, catalyst, product yield, time and utilities, which are interrelated and modifying one alters the others.
- Examining each unit independently can help identify opportunities for technical improvements. In addition, they can be reused in other studies.
- Based on the material balance principle, the in and out flows are balanced for each process unit.
- The exergy of pure substances, mixtures and utilities is calculated. The total exergy of the system is equal to the chemical exergy of material and the exergy of utilities.
- The exergy of each process stream is calculated to obtain an exergy flow diagram of the process which allows identifying material and waste energy, detecting areas needing technological improvements, measuring the potential reactivity and quality.
- The maximum improvement in the exergy efficiency for a process or system is determined using equation (17).
- Mass and energy flow rate values were calculated using the equations (1)–(5);
- Minor flows were neglected;
- Effects of kinetic, potential and chemical exergies were neglected;
- Exergy values were calculated using the equations (6)–(12) given in the theoretical section; energy and exergy efficiencies for each main unit in the system were calculated from equations (12)–(16).

Table 1
Flow velocities in m/s.

Description of flow	Velocity (m/s)
V_8	0.75
V_9	0.66
V_{10}	0.50
V_{11}	0.50
V_{12}	0.66
V_{13}	0.42
V_{14}	0.25
V_{15}	1.00

Table 2
Energy and exergy flows in the paper and pulp mill.

	Stream identification	$m \cdot C_p$ [kW/K]	T [K]	E [kW]	$\dot{E}x$[kW]
1	Waste paper	1.875	293	549.4	549.4
2	Water	19.875	333	6618.4	5855.3
3	Waste pulp	0.094	318	29.9	27.4
4	Waste pulp	1.791	318	569.5	529.0
5	Pulp	11.586	318	3684.3	3423.0
6	Waste pulp	3.306	308	1018.2	970.9
7	Screened pulp	8.532	308	2628.0	2506.0
8	Screened pulp	2.133	308	657.0	626.5
9	Waste pulp	0.388	305	118.3	114.0
10	Washed pulp	2.042	305	622.8	599.2
11	Washed pulp	8.167	305	2490.9	2397.0
12	Refined pulp	8.167	303	2474.6	2403.8
13	Stock	8.167	299	2441.9	2394.4
14	Waste water	5.245	297	1557.8	1542.6
15	Dewatered stock	2.884	297	856.5	848.2
16	Waste water	0.835	295	246.3	243.7
17	Pressed stock	2.090	295	616.6	610.5
18	Sat. steam	13.398	428	5734.3	1587.3
19	Sat. steam	14.204	398	5653.2	1332.9
20	Steam	1.450	307	445.2	19.3
21	Hard paper	1.688	307	518.2	493.9

Table 3
Energy losses and energy efficiencies in the pulp and paper mill.

Unit	Energy losses [kW]				Energy efficiency [%]
	Direct	%	Total	%	η_{en}
DI	5684.4	88.9	6283.6	60.5	37.0
SC	103.1	1.6	1121.2	10.8	70.1
HY	18.8	0.3	137.2	1.3	94.8
RE	66.3	1.0	66.3	0.6	97.4
SPU	92.7	1.4	92.7	0.9	96.3
WP	107.3	1.7	1665.2	16.0	34.0
RO	73.8	1.2	319.4	3.1	65.8
CY	248.4	3.9	693.6	6.7	41.5

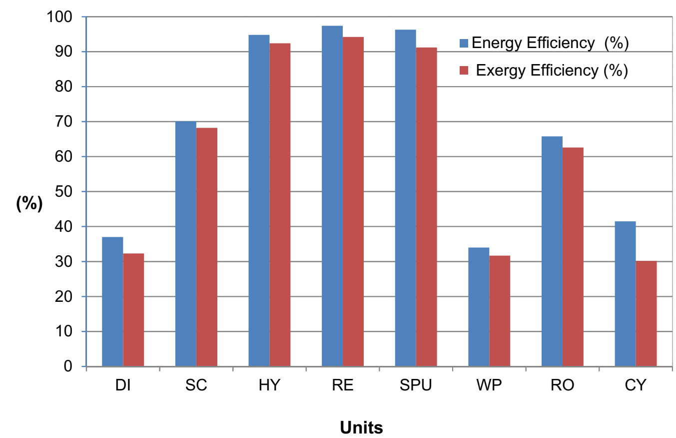


Fig. 3. Variation of energy and exergy efficiencies in the pulp and paper mill.

4.2. Energy and exergy analysis

The heat capacities, temperatures, and energy and exergy values for each stream are given in Table 2. The quantitative waste energy and energy efficiencies for the entire mill are tabulated in Table 3. The biggest waste energy, as 60.5 percent is realised in the DI, as 60.5 per cent. The energy efficiencies vary between 34% and 97.4% in all sub-processes of a PPM plant. The total losses constitute unutilised flows. The quantitative exergy losses and exergy efficiencies for the entire mill are tabulated in Table 4. In addition to this the biggest exergy losses obtained in the DI as 60.8 percent, while the exergy efficiencies vary between 30.2% and 98%.

The energy and exergy efficiency values are shown in Fig. 3. Based on the actual values, for the pulp and paper units were obtained as of 34.0%, to 97.4%, while the corresponding exergy efficiency values for those were found to be from 30.2% to 94.2%. These values have indicated that exergy utilisation in the PPM process was similar to energy utilisation except for CY unit. In this unit, exergy utilisation was even worse than energy utilisation.

On the other hand, the waste-paper cooking in the continuous digester and board drying on the steam-heated cylinders are the largest. Waste energy, exergy losses and the improvement potential in the PPM units are given in Fig. 4. The biggest energy, exergy losses and the improvement potential were obtained in the Digester unit. The results of the energy analyses using the Sankey diagram are obtained, as shown in Fig. 5, whereas the results of exergy analyses using the Grossman diagram are presented in Fig. 6.

Two peaks in the energy and exergy analyses are observed at the digester. These calculations show that the energy input to the digester has the highest improvement potential because more than 63% of the energy and 68% of the exergy are lost in the digester. The efficiencies at this point are estimated to be only approximately 35%.

In the evaporative drying process, the energy and exergy efficiencies are significantly lower, 41.5% and 30.2%, respectively. This is the result of requiring large quantities of steam for heating purposes. Drying is the most energy-intensive step associated with papermaking operations, making it the least efficient process in the PPM from an exergy standpoint.

Washing, refining and stock preparation exhibit energy and exergy losses relatively smaller than the digesting process, varying between 94.8% and 92.2%, respectively, as shown in Fig. 4. The resulting waste energy are higher than the exergy losses through these sub-processes and are closely linked to the use of hot water with a low energy content that must be supplied in large quantities.

Based on the calculated data shown in Fig. 3, the exergy efficiencies (92.4%, 94.2% and 91.2%) seem to be lower than the energy efficiencies (94.8%, 97.4% and 96.3%, respectively). The unutilised outflows, i.e., the difference between the total and direct losses, are essentially a much smaller heat source. They constitute 38.4% of the total losses and 33.6% of the exergy.

The results of the exergy analysis in the selected PPM as a part of the sulphide-cellulose preparation plant are obtained by applying the first law of thermodynamics and neglecting the heat losses from the pyrite reactor that are due to insufficient insulation.

The exergy analysis indicates that heat losses from the pulp and paper mill result from internal irreversibilities, i.e., combustion and heat transfer with high temperature gradients, and external irreversibilities, i.e., heat losses to the ambient surroundings. These

Table 4
Exergy losses and exergy efficiencies in the pulp and paper mill.

Unit	Exergy losses [kW]				Exergy efficiency [%]
	Direct	%	Total	%	ε
DI	5672.2	83.4	6228.6	60.8	32.3
SC	16.1	0.2	987.0	9.6	68.2
HY	4.0	0.1	110.0	1.1	92.4
RE	49.4	0.7	49.4	0.5	94.2
SPU	71.3	1.1	71.3	0.7	91.2
WP	82.1	1.2	1624.7	15.9	31.7
RO	74.5	1.1	318.2	3.1	62.6
CY	834.9	12.2	854.2	8.3	30.2

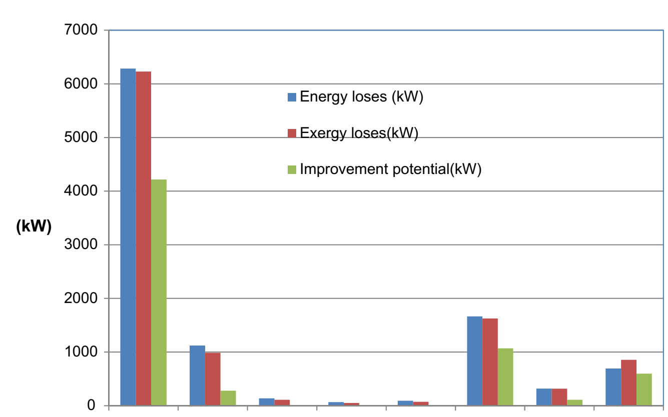


Fig. 4. Energy, exergy loses and improvement potential in the pulp and paper mill units.

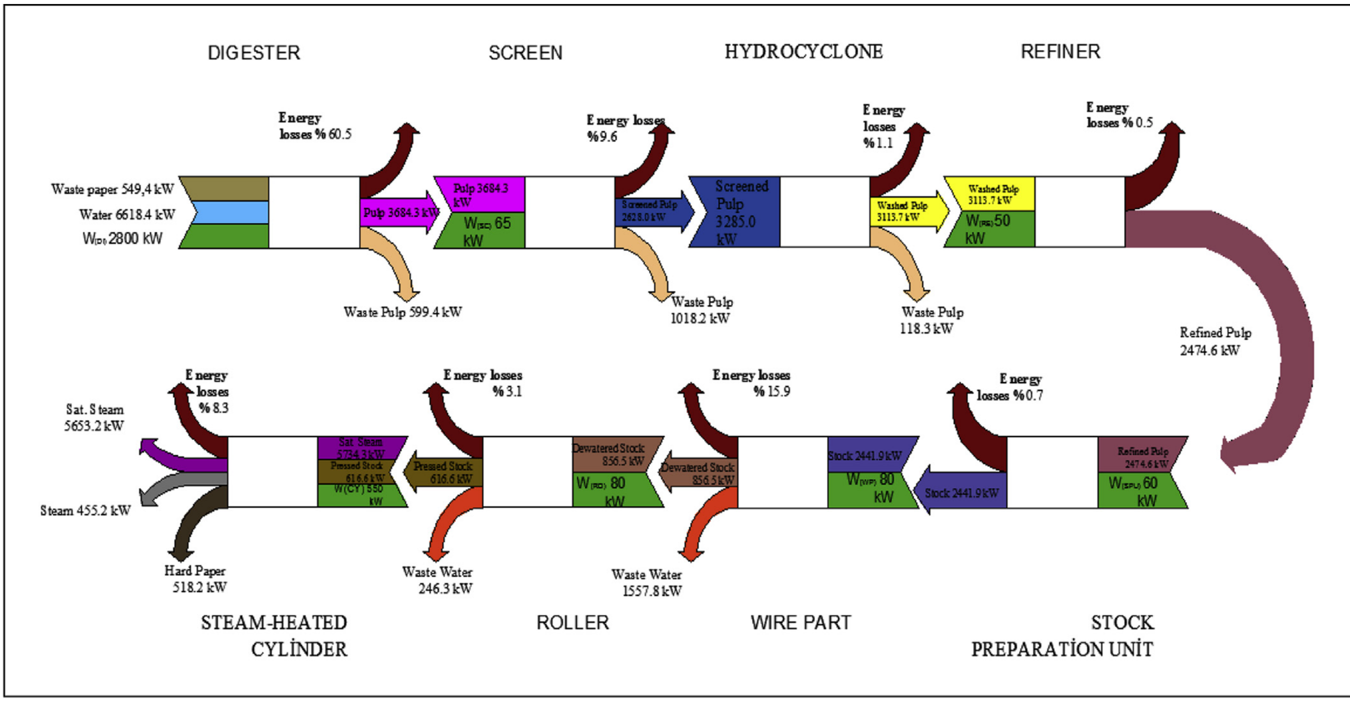


Fig. 5. Sankey (energy flow) diagram of the pulp and paper mill units studied.

losses can be prevented by reducing the fuel combustion velocity and utilising much more effective thermal insulation.

The enthalpy analysis shows that there is no waste energy in the waste heat recovery boiler. However, the completed exergy analysis claims an exergy loss of 30%. Based on this information, it is concluded that an economiser should be integrated into the waste heat recovery boiler, and the hourly steam production rate should be increased by 15–20% (450 kg/h) by cooling the temperature of off-gas to 100–150 °C.

4.3. Results obtained comparison with the results of previous studies

Table 5 illustrates a comparison of the energy and exergy efficiency values for Pulp and Paper Industry [1,9,10,21,22]. Evaluating the results of this table indicates that paper and pulp industry overall energy efficiencies ranged from 34.00 to 97.40%, with average values of 69.35% according to subsectors. On the other hand, evaluating in terms of the exergy efficiencies, the results of

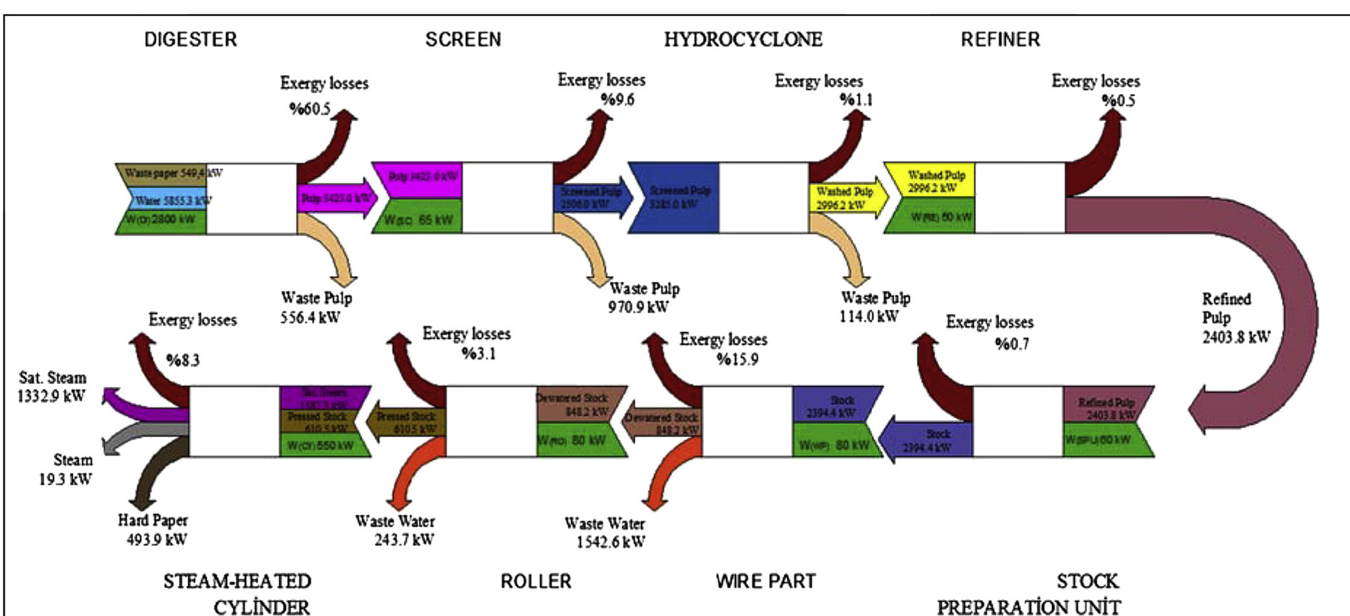


Fig. 6. Grassmann (exergy loss and flow) diagram of the pulp and paper mill units studied.

Table 5
Results obtained comparison with the results of previous studies.

Process	Sub-process	Energy efficiencies (%)	Exergy efficiencies (%)	References
Paper industry	Paperboard mills	73	37.6	[9]
	Pulp mills	71.8	40.9	
	Paper mills	74.6	42.9	
Pulp and paper industry	Total pulp and paper	72.16	NA	[1]
Pulp and paper industry	Total pulp and paper	73.16	NA	[22]
Pulp and paper mill with cogeneration plant	Evaporator line	NA	28.82	[21]
	Liquor heat treatment	NA	34	
	Recovery boiler	NA	11.96	
	Turbo generator	NA	85.1	
Sulphide-pulp preparation units	Pyrite reactor	NA	34.10	[10]
	Waste heat recovery boiler	NA	70.71	
	Mixing tank	NA	98.4	
	Washing tower	NA	17.20	
	Gas coolers	NA	12.80	
Pulp and paper industry	Digester	37.0	32.3	In this study
	Steam-heated cylinder	70.1	68.2	
	Hydrocyclone	94.8	92.4	
	Refiner	97.4	94.2	
	Roller	96.3	91.2	
	Screen	34.0	31.7	
	Stock preparation unit	65.8	62.6	
	Wire part	41.5	30.2	

this table shows that paper and pulp industry overall exergy efficiencies determined from 11.96 to 98.40%, with average values of 52.20%. Among the sub-process investigated, the refiner process had the highest efficiencies, followed by the roller, the hydrocyclone, paper mills and total pulp and paper process. Besides this, the screen and digester process had about equal and fairly low energy efficiencies. By comparison, low exergy efficiencies are reported to be about 11.96% for recovery boiler and 12.80% for gas coolers, while high exergy efficiencies are 98.0% for refiner, 98.4% for mixing tank.

5. Conclusion

This study has shown that high-quality industry-level analyses are key factors in improving the energy and exergy efficiencies for the papermaking sector, which is very energy-intensive and sophisticated. The actual data derived from a PPM Plant have enabled us to analyse mass and energy balances, as well as energy and exergy utilisation efficiencies through the selected system.

The results indicate that the exergy efficiencies through the recycled waste paper cooking process in the digester, the wiring portion of the dewatering process and, especially, drying by evaporation remain to be studied in order to realise additional system energy gains.

According to the first law of thermodynamics and the exergy analysis, throttling occurring at a constant enthalpy with no waste energy causes an exergy loss of 22%. However, it is recommended that this loss be used to produce steam at a regular pressure. In all sub-processes of a PPM Plant, the energy efficiencies vary between 34.0% and 97.4%, whereas the exergy efficiencies vary between 30.2% and 94.2%. The heat losses from the surface of the PPM, based on calculations for estimating the conduction, convection and radiation modes, are approximately 14.300 MJ/h. This calculation also identifies the energy-saving potential by an energy recovery of 15.70% of the total input energy into the PPM. The results show that the highest improvement potential possible is 4216 kW for the DI.

This study mainly indicates that exergy utilisation is significantly weaker than is energy utilisation. Future avenues of study should include the implementation of current technologies that can affect the exergy efficiency.

In conclusion, based on the energy and exergy flow analyses, the exergy output can be improved by directing future efforts primarily toward obtaining further measurements to achieve more efficient energy utilisation in PPMs.

References

[1] Hong GB, Maa CM, Chen HW, Chuang KJ, Chang CT, Su TL. Energy flow analysis in pulp and paper industry. Energy 2011;36:3063–8.

[2] Van Beukering PJH, Bouman MN. Empirical evidence on recycling and trade of paper and lead in developing countries. World Development 2001;29(10):1717–37.

[3] Berglund C, Söderholm P. Complementing empirical evidence on global recycling and trade of waste paper. World Development 2003;31(4):743–54.

[4] Berglund C, Söderholm P, Nilsson M. A note on inter-country differences in waste paper recovery and utilization. Resources, Conservation and Recycling 2002;34:175–91.

[5] Niutanen V, Korhonen J. Management of old landfills by utilizing forest and energy industry waste flows. Journal of Environmental Management 2002;65:39–47.

[6] Byström S, Lönnstedt L. Paper recycling: environmental and economic impact. Resources. Conservation and Recycling 1997;21:109–27.

[7] Brown D, Marechal F, Paris J. A dual representation for targeting process retrofit, application to a pulp and paper process. Applied Thermal Engineering 2005;25:1067–82.

[8] Jönsson J, Berntsson T. Analyzing the potential for implementation of CCS within the European pulp and paper industry. Energy 2012;44:641–8.

[9] Al-Ghandoor AA, Phelan PE, Villalobos R, Jaber JO. Energy and exergy utilizations of the U.S. manufacturing sector. Energy 2010;35:3048–65.

[10] Gemci T, Öztürk A. Exergy analysis of a sulphide-pulp preparation process in the pulp and paper industry. Energy Conversion and Management 1998;39(16):1811–20.

[11] Beer JD, Worrell E, Blok K. Long-term energy-efficiency improvements in the paper and board industry. Energy 1998;23:121–42.

[12] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical, and metallurgical processes. New York: Hemisphere; 1988.

[13] Wall G. Exergy flows in industrial processes. Energy 1988;13(2):197–208.

[14] Dincer I. Thermodynamics, exergy and environmental impact. Energy Sources 2000;22:723–32.

[15] Rosen MA, Le MN, Dincer I. Efficiency analysis of a cogeneration and district energy system. Applied Thermal Engineering 2005;25:147–59.

[16] Dincer I. The role of exergy in energy policy making. Energy Policy 2002;30:137–49.

[17] Kotas TJ. The exergy method of thermal plant analysis. Reprint ed.. Malabar, Florida: Krieger Publishing; 1995

[18] Wall G. Exergy conversion in the Japanese society. Energy 1990;15(5):435–44.

[19] Sarimveis HK, Angelou AS, Retsina TR, Rutherford SR, Bafas GV. Optimal energy management in pulp and paper mills. Energy Conversion and Management 2003;44:1707–18.

[20] Persson J, Berntsson T. Influence of seasonal variations on energy-saving opportunities in a pulp mill. Energy 2009;34(10):1705–14.

[21] Cortés E, Rivera W. Exergetic and exergoeconomic optimization of a cogeneration pulp and paper mill plant including the use of a heat transformer. Energy 2010;35:1289–99.
[22] Chen HW, Hsu CH, Honga GB. The case study of energy flow analysis and strategy in pulp and paper industry. Energy Policy 2012;43:448–55.
[23] Giraldo L, Hyman B. An energy process-step model for manufacturing paper and paperboard. Energy 1996;21(7–8):667–81.
[24] Szabo L, Soria A, Forsström J, Kerönen JT, Hytönen E. A world model of the pulp and paper industry: demand, energy consumption and emission scenarios to 2030. Environmental Science & Policy 2009;12:257–69.
[25] Fleiter T, Fehrenbach D, Worrell E, Eichhammer W. Energy efficiency in the German pulp and paper industry – a model-based assessment of saving potentials. Energy 2012;40:84–99.
[26] Sorgüven E, Özilgen M. Energy utilization, carbon dioxide emission, and exergy loss in flavored yogurt production process. Energy 2012;40(1):214–25.
[27] Utlu Z, Hepbaşlı A. Review on analyzing and evaluating the energy utilization efficiency of countries. Renewable and Sustainable Energy Reviews 2007;11(1):1–29.
[28] David C, Bligh V, Ugursal I. Extended exergy analysis of the economy of Nova Scotia, Canada. Energy 2012;44(1):878–90.
[29] Utlu Z, Hepbaşlı A. A review and assessment of the energy utilization efficiency in the Turkish industrial sector using energy and exergy analysis method. Renewable and Sustainable Energy Reviews 2007;11(7):1438–59.
[30] Ertesvåg I. Energy, exergy, and extended – exergy analysis of the Norwegian society 2000. Energy 2005;30(5):649–75.
[31] Utlu Z, Hepbasli A, Turan M. Performance analysis and assessment of an industrial dryer in ceramic production. Drying Technology 2011;29(15):1792–813.
[32] Gaggioli RA, Petit PL. Use the second law first. Chemtech 1977;7:496–506.
[33] Cornelissen RL. Thermodynamics and sustainable development: the use of exergy analysis and the reduction of irreversibility [PhD thesis]. The Netherlands: University of Twente; 1997.
[34] Wall G. Exergy tools. In: Proceedings of the Institution of Mechanical Engineers. Wilson applied science & technology abstracts plus text; 2003. p. 125–36.
[35] Torres EA, Gallo WLR. Exergetic evaluation of a cogeneration system in a petrochemical complex. Energy Conversion and Management 1998;16(18):1845–52.
[36] Van Gool W. Energy policy: fairy tales and factualities. In: Soares ODD, Martins da Cruz A, Pereira G Costa, Soares IMRT, Reis AJPS, editors. Innovation and technology – strategies and policies. Dordrecht: Kluwer; 1997. p. 93–105.
[37] Hammond GP, Stapleton AJ. Exergy analysis of the United Kingdom energy system. Proceedings of the Institution of Mechanical Engineers 2001;215(2):141–62.
[38] Laurijssen J, De Gram FJ, Worrell E, Faaij A. Optimizing the energy efficiency of conventional multi-cylinder dryers in the paper industry. Energy 2010;35(9):3738–50.
[39] Francis DW, Towers (MT), Browne TC. Energy cost reduction in the pulp and paper industry – an energy benchmarking perspective. Pulp and Paper Research Institute of Canada, ISBN 0-662-66163-X; 2002. p. 21.

Nomenclature

C_p: specific heat capacity [kJ/kg K]
E: energy (kJ)
$\dot{E}$: energy rate (kW)
ex: specific exergy (kJ/kg)
Ex: exergy (kJ)
$\dot{E}x$: exergy rate (kW)
h: specific enthalpy (kJ/kg) or heat convection coefficient (W/m^2 K)
I: irreversibility, exergy consumption (kJ)
$\dot{I}$: irreversibility rate, exergy consumption rate (kW)
$\dot{I}P$: improvement potential rate for exergy (kW)
$\dot{m}$: mass flow rate [kg/s]
Q: heat transfer (kJ)
$\dot{Q}$: heat transfer rate (kW)
S: entropy [kW/K]
T: stream temperature [K]
T_o: reference temperature [293 K]
v: flow velocity [m/s]
W: work [kW]
$\dot{W}$: work rate or power (kW)

Greek letters
η: energy efficiency (%)
ε: exergy efficiency (%)
ψ: flow exergy (kJ/kg)

Indices
inc: incompressible
in: input
0: dead state or reference environment
out: outlet, existing
DI: digester
CY: steam-heated cylinder
HY: hydrocyclone
RE: refiner
RO: roller
SC: screen
SPU: stock preparation unit
WP: wire part