Energy and Exergy Analysis of Steam Boiler and Autoclave in Fiber Cement Process

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Abstract
The fiber cement composite production process consumes extremely high fuel especially boiler and autoclave leading to the release of a lot of waste energy. In this study, the concept of energy and exergy utilization is analyzed and illustrated in the form of the Sankey diagram. It was found that the energy and exergy efficiencies of the boiler were 72.04 and 69.98%, respectively. The exergy destruction of the boiler system is 30% or 3.89 MW. Which can also be represented in the Power Available Diagram (PAD). In the exergy analysis, there are 2 methods in reducing the energy loss of the boiler by increasing the steam outlet temperature or reducing the temperature of the exhaust gas of the boiler. For the autoclave system, the energy analysis showed the total energy input at 43.67 GJ/batch. The three main energy losses are; the exhaust steam (49.74% or 23.74 GJ/batch), condensate (16.42% or 7.83 GJ/batch) and autoclave shell heat loss (13.67% or 6.25 GJ/batch). For the exergy, the exergy destruction in the autoclave is at 87.14%. However, the PAD of the autoclave cannot present the relation of the exergy loss. The main causes of the exergy destruction are the three main energy losses; the exhaust steam (50.80%), condensate (16.47%) and autoclave shell loss (10.01%) respectively.

Keywords: *Exergy analysis, Autoclave, Energy and exergy*

1 Introduction

The fiber cement process is an interesting process as it uses a lot of energy and has a high waste energy release at the same time. Mahaphant Fiber-cement Public Company Limited is the leader of fiber cement construction materials in Thailand with an existing capacity of 500,000 ton/year. The overall process is illustrated in Figure 1.

Fiber cements process has extremely high fuel consumption, in the steam boilers with almost 85% of the steam being used in the autoclave. Boiler efficiency therefore has a great influence on heating-related energy savings. It is important to maximize the heat transfer to the water and minimize the heat losses in the boiler. Various heats lost from normal operation were reported, including hot flue gas losses, radiation losses and, blow-down losses [3] and etc. To optimize the

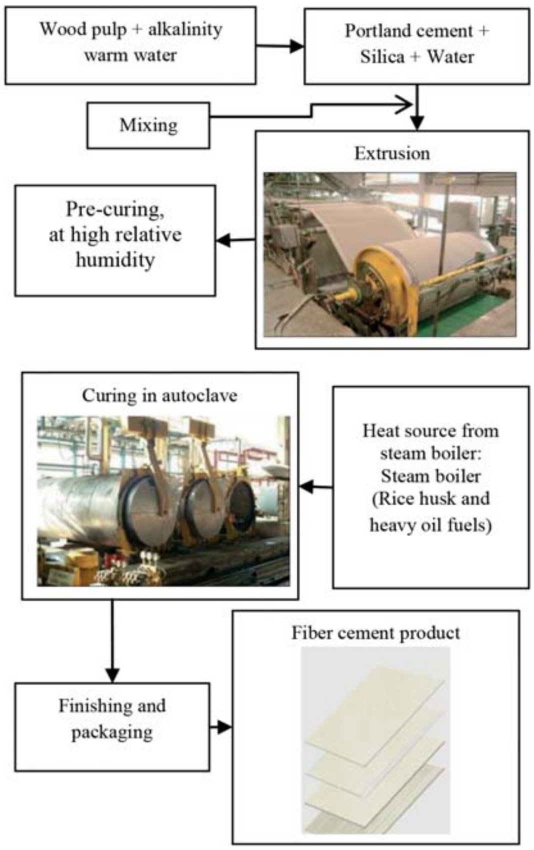


Figure 1: Fiber cement process diagram [1].

operation of a boiler in the process, it is necessary to identify the point source of energy losses. A significant amount of energy lost through flue gases as all the heat produced by the burning fuel cannot be transferred to water or steam in the boiler. The main source of fuel used in the main boiler is biomass (rice husk). At normal operation of the plant, the boiler is used to heat up water from ambient temperature (25°C) to steam at average pressure of 10 bars, requiring the average of the rice husk feed rate of 3 ton/hour to produce steam at 15 ton/hour, which is used to supply the autoclave section [3]. The heat associated with these steams will be quantified in this work. In the autoclave section, the steam consumption of the autoclave is used to heat up the material inside. The total steam consumption for each batch of operation is about 13 ton/hour. The exhaust steam was estimated to be 8 ton/hour at average 130°C. The continuous condensate from the autoclave is about 8 – 9 ton/batch at 130°C. The heat lost fromthe wall of the autoclave is also expected to be significant and will be quantified.

The first law of thermodynamics is conventionally used to analyze the energy utilization, but it is unable to account the quality aspect of energy. That is where exergy analysis becomes relevant. Exergy is the consequent of the second law of thermodynamics. It is a property that enables us to determine the useful work potential of a given amount of energy at some specified state. Exergy analysis has been widely used in design, simulation and performance evaluation of thermal and thermo-chemical systems. The energy use of a country has been assessed using exergy analysis to gain insight of its efficiency and potential for further improvement. Known energy sources have been exhausted rapidly at the moment time, in addition raising the energy costs [4]. Several studies are currently going on controlling the mechanisms responsible for the energy degradation to minimize the system losses and to reduce the costs [5]. As energy analysis fails to indicate both the energy transformation and the location of energy degradation, in recent years, emerged a growing interest in the principle of special ability to measure different types of energy to work and popularly known as exergy [6]. Extensive application of exergy analysis can lead to reduce the use of natural resources and thus, to decrease theenvironmental pollution. The main purpose of exergy analysis is to detect and assess quantitatively the thermodynamic imperfections in thermal and chemical processes. The exergy method of thermodynamic analysis is based upon both the first and the second laws of thermodynamics together, while the energy analysis is based upon the first law only. It is a feature of the exergy concept to allow quantitative assessment of energy degradation [7].

Dincer et al. [8] discussed that the exergy appears to be a key concept since it is a linkage between the physical and engineering world and the surrounding environment and expresses the true efficiency of engineering systems, which makes it a useful concept to find improvements. As a complement to the present materials and energy balances, exergy calculations can provide increased and deeper insight into the process, as well as new unforeseen ideas for improvements. Consequently, it can be highlighted that the potential usefulness of exergy analysis in sectoral energy utilization is substantial and that the role of exergy in energy policy making activities is crucial [9].

1.1 *Energy and exergy analysis*

This section presents some of the key aspects of thermodynamics, in terms of energy and exergy, relevant to the current study.

The total exergy of system E can be divided into four components: physical exergy E^{PH}, kineticexergy E^{KN}, potential exergy E^{PT}; and chemical exergy E^{CH}:

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \quad (1)$$

We may write the total specific exergy on a mass basis given by

$$\varepsilon = \varepsilon^{PH} + \varepsilon^{KN} + \varepsilon^{PT} + \varepsilon^{CH} \quad (2)$$

Normally, if there is no change in kinetic and potential energies as well as in the chemical composition, we end up with physical exergy only as follows:

$$\varepsilon^{PH} = (h - h_0) - T_0 (s - s_0) \quad (3)$$

Where h and s are the specific enthalpy and entropy, respectively and T is the temperature. The subscript ‘‘0’’ denotes conditions of the reference environment [10].

1.2 *Definition of energy and exergy efficiencies*

In the analysis, it is important to understand the difference between energy and exergy efficiencies. Consider a control volume at steady state for which the energy and exergy equations can be written, respectively, as

Energy input − Energy output
= Energy accumulation (4)

Exergy input − Exergy output − Exergy consumption
= Exergy accumulation (5)

In these equations, the destruction term is referred to exergy destruction due to internal irreversibilities. From either viewpoint, energy oravailability, a gauge of how effectively the input is converted to the product is the ratio (product/input), that is

η = (Energy in products/Total energy input) (6)

ψ = (Exergy in products/Total exergy input) (7)

The parameter ψ weights energy flows by accounting for each in terms of availability. It stresses that both losses and internal irreversibilities need to be dealt with improved performance.In many cases, it is the irreversibilities to deal with more significance and more difficulty.

1.3 *Basic quantities for exergy analysis*

The following subsection discusses some basic quantities and mathematical relations related to exergy.

1.3.1 Exergy of a flowing stream of matter

Consider a flowing stream of matter at temperature T; pressure P; chemical composition μj of species j; mass m; specific enthalpy h; specific entropy s; specific kinetic energy ke; potential energy pe; and mass fraction x_j of species j: Assuming a conceptual environment in an equilibrium state with intensive properties at T_0; P_0 and μj_{00}: And, assuming the environment to be large enough such that its intensive properties are negligibly affected by any interactions with the system. With the above considerations, the specific exergy of the flowing stream of matter can be expressed as

$$\varepsilon = \left[ke + pe + (h - h_0) + T_0 (s - s_0)\right] + \left[\sum_j (\mu_{j0} - \mu_{j00}) x_j\right] \quad (8)$$

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 extracted from a flowing stream as it is brought to the environmental state. The chemical $[\sum_j (\mu_{j0} - \mu_{j00}) x_j]$ is the maximum available work extracted from the stream as it is brought from the environmental state to the dead state.

1.3.2 Exergy of heat

The amount of thermal exergy transfer associated with heat transfer Q_r across a system boundary r at a constant temperatureT_r is

$$E^Q = \left(1 - \frac{T_0}{T_r}\right) Q_r \quad (9)$$

1.3.3 Exergy of work

The exergy associated with work is

$$E^W = W \quad (10)$$

1.3.4 Exergy consumption

The amount of exergy consumed due to irreversibilities during a process is

$$I = T_0\, S_{gen} \quad (11)$$

1.4 *The reference environment*

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, and is a sink or source for heat and materials, and experience only internal reversible processes in which its intensive properties (i.e. temperature T_0, pressure P_0 and chemical properties μj_{00} for each of the j component) remains constant. Assume that, based on weather and climate condition in Malaysia can be used for Thailand. Following the minor modifications of the Gaggioli and Petit's model [11] which is recommended by Dincer [9], this analysis used T_0 = 25°C as the surrounding temperature, P_0 = 100 kPa as the surrounding pressure and the chemical composition is taken to be air saturated with water vapor, and the condensed phases are used at 25°C and 100 kPa: water (H_2O), gypsum ($CaSO_4 \cdot 2H2O$) and limestone ($CaCO_3$) [8].

2 Materials and Methods

This work is study the mass and energy balance and also exergy of the main energy consume equipment in the fiber cement production process. The biomass (rice husk) boiler and autoclave are considered and compared the result with the other research the industrial boiler of Saidur et al. [12].

2.1 *Energy and exergy analysis of boiler*

The boiler is usually well insulated, that cause less heat dissipation to the surrounding. It also as no involvement to do any kind of work (w = 0). Also, the kinetic and potential energies of the fluid streams are usually negligible. Then only total energies of the incoming streams and the outgoing mixture remained for analysis. The conservation of energy principle requires that these two equal each other. Besides, the sum of the incoming mass flow rates will be equal to the mass flow rates of the outgoing mixture. Taking mass flow rate for fuel as m_f, mass flow rate for air as m_a, mass flow rate forsteam products as m_{st}, mass flow rate for water as m_w, and m_{bd} = mass flow rate for blow down, energy balance can be expressed as:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = 0 \quad (12)$$

$$\dot{E}_{in} = \dot{E}_{out} \quad (13)$$

$$\dot{m}_f h_f + \dot{m}_a h_a + \dot{m}_w h_w = \dot{m}_{st} h_{st} + \dot{m}_{bd} h_{bd} \quad (14)$$

Where, h_f = specific enthalpy of fuel, kJ/kg, h_a = specific enthalpy of air, kJ/kg, h_{st} = specific enthalpy of steam products, kJ/kg, h_w = specific enthalpy of water, kJ/kg, h_{bd} = specific enthalpy of blow down, kJ/kg. The maximum power output or reversible power is determined from the exergy balance applied to the boiler considering boundary with an environment temperature of T_0 (T_0 = 25°C) and by assuming the rate of change in exergy in the boiler's system is zero. The exergy balance formulations have been established using methodology developed by Aljundi [13], Dincer and Rosen [14].

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = \frac{dX_{system}}{dt} = 0 \quad (15)$$

$$\left(\dot{m}_f \varepsilon_f + \dot{m}_a \varepsilon_a + \dot{m}_w \varepsilon_w\right) - \dot{m}_{st}\varepsilon_{st} - \dot{m}_{bd}\varepsilon_{bd} - I_C = 0 \quad (16)$$

$$I_C = \left(\dot{m}_f \varepsilon_f + \dot{m}_a \varepsilon_a + \dot{m}_w \varepsilon_w\right) - \left(\dot{m}_{st}\varepsilon_{st} + \dot{m}_{bd}\varepsilon_{bd}\right) \quad (17)$$

Where, I_C = Exergy destruction, ε_a, ε_f, εw, ε_{bd} and ε_{st} are exergy of air, fuel, water, blow down and steam products, respectively.

Figure 2 is shown the methodology of this work.

2.2 *Power Availability Diagram (PAD)*

The original PAD is proposed for better exergy loss visualization. In 1995, Homsak and Glavic introduced Power Availability Diagram (PAD) [15], the plot of temperature against the exergy flow of two working units, a turbine and a compressor, of evaporative cycle.

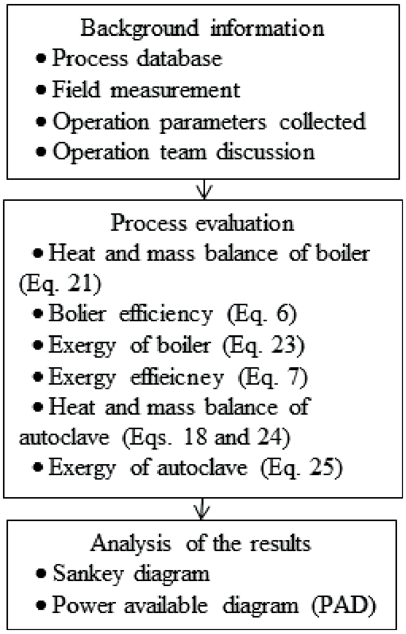


Figure 2: Methodology.

The y-axis of the PAD is the temperature, which is easier to interpret in the context of the process than the energy donor and acceptor. The x-axis of PAD is the absolute exergy (referred to the standard condition).

Therefore, the user can read and compare the exergy-temperature profile of energy donor and acceptor and the exergy loss (or change) of each unit operation in a power cycle.

The information from the boiler can also be plotted in the PAD form. It provided the information of the exergy loss of the system. The difference of the projection between the exergy of hot gas and fresh water represented the exergy loss of the boiler system.

2.3 *Energy and exergy analysis of autoclave*

Autoclave is used to produce the fiber cement composites. The material proportions (cement,cellulous fiber, gypsum, silica sand and water) are designed, mixed and formed to be green sheets (composite board before accelerated in the autoclave). The green sheets are delivered (with steel pallets on the stack cars) and arranged into the autoclave. After autoclave is fully with green sheets, the main gate is closed and sealed. The steam is charged into the autoclave, maintained and released following the operation graph. The total steam usage for one batch operation is about 13 ton steams which 60 ton fiber cements production. Same as the analysis of the boiler, the process information was collected from filed measurement, control panel and laboratory of the plant as average for one week operation. Table 1 showed the composition of fiber cement.

Table 1: Fiber cement composite compositions

Composition	Percentage (%)
Ordinary portland cement	28.0
Fiber	8.0
Grinded sand	28.0
Gypsum	36.0

After finished the process, the steam and condensate are exhausted from the autoclave and the fiber cement product delivered to other process. The energy balance and exergy destruction of the autoclave system can be applied with Eqs. (12) and (15) as shown in Eqs. (18) and (19), respectively.

$$\dot{m}_{fc}h_{fc} + \dot{m}_{st}h_{st} + \dot{m}_{as}h_{as} + \dot{m}_{sp}h_{sp} + \dot{m}_{sc}h_{sc} = \dot{m}_{fc}h_{fc} + \dot{m}_{fcm}h_{fcm} \quad (18)$$

$$I_C = \left(\dot{m}_{fc}\varepsilon_{fc} + \dot{m}_{st}\varepsilon_{st} + \dot{m}_{as}\varepsilon_{as} + \dot{m}_{sp}\varepsilon_{sp} + \dot{m}_{sc}\varepsilon_{sc}\right) - \left(\dot{m}_{fc}\varepsilon_{fc} + \dot{m}_{fcm}\varepsilon_{fcm}\right) \quad (19)$$

Where subscript fc = fiber cement, fcm = fiber cement moisture, as = autoclave shell, sp = steel pallets and sc = stack cars, respectively.

3 Results and Discussion

3.1 *Energy and exergy of the boiler*

Table 2 showed the mass flow rate, temperature, enthalpy and entropy of the boiler system. The process information was collected from filed measurement and control panel of the plant as average of one week operation. The average of the heating value of the rice husk is equal to 15,473.22kJ/kg rice husk based on the analysis of the plant. The study boundary of the boiler is included the internal heat exchanger. The overall mass and energy balance of the boiler at Mahaphant Fiber-Cement Public Company Limited was made as shown in the Figure 3.

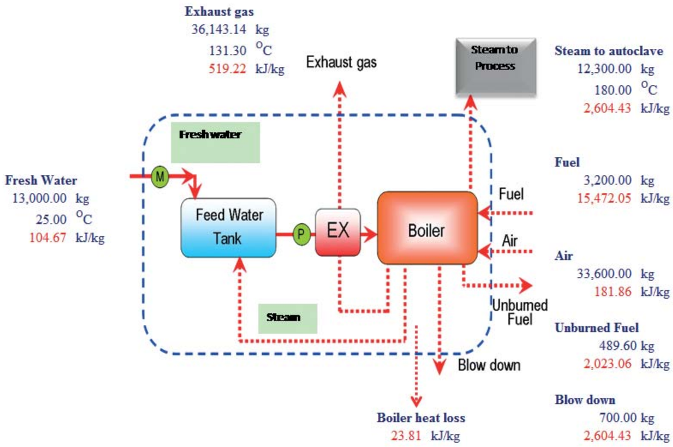


Figure 3: The overall mass and energy balance of steam boiler.

Table 2: Mass flow rate, temperature, enthalpy and entropy of the boiler

Substance	Mass flow rate (kg/hr.)	Temperature (°C)	Enthalpy (MW)	Enthalpy (kJ/kg)	Entropy (kJ/kg·°C)
Inlet					
Fresh feed water	13,000	25	0.38	104.67	-
Rice husk	3,200	35	12.27	15,473.22	1.76
Air	33,600	35	0.40	181.86	1.75
Outlet					
Steam	12,300	180	8.90	2,604.43	3.81
Blow down steam	700	180	0.51	2,604.43	3.81
Exhaust gas	36,143	131	3.04	519.22	1.65
Unburnt Rice husk	490	180	0.33	2,023.06	2.48
Heat loss	-	50	0.08	23.81*	-

* Heat loss from steam boiler body is calculated based on kilogram of steam production.

The energy input of the system in Table 2 can be calculated as:

$$\dot{E}_{in} = \dot{m}_f h_f + \dot{m}_a h_a + \dot{m}_w h_w \tag{20}$$

$$\dot{E}_{in} = \left[\left(\dot{m}_{fd} h_{fd} + \dot{m}_{fm} h_{fm} + \dot{m}_{fd} LHV\right)\right] + \left[\left(\dot{m}_{ad} h_{ad} + \dot{m}_{am} h_{am}\right)\right] + \dot{m}_w h_w \tag{21}$$

Where, subscript fd = fuel dry, fm = fuel moisture, ad = air dry and am = air moisture, respectively. Bouapetch [16] reported calculation of the energy input and output.

The information in Table 2 showed that the total energy input of the boiler is equal to 13.05 MW. The product energies are the energy of steam and blow down equal to 8.9 and 0.51 MW respectively. The energy efficiency of the boiler is 72.04% as calculated following Eq. (6)

$$\eta = \left(\frac{\text{Energy in products}}{\text{Total energy input}}\right) = \frac{(8.9 + 0.51)}{(12.27 + 0.4 + 0.38)} = 0.7204 = 72.04\%$$

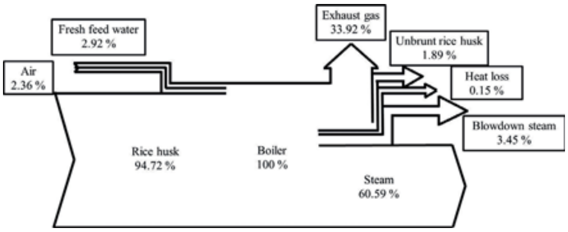
In term of the exergy analysis, the exergy destruction of the boiler is estimated by using the Eq. (17). It is assumed that the boiler operates in the steady-flow process since there is no change in the process with time at any point, thus change of mass and energy of the control volume of the boiler is

$$I_C = \left(\dot{m}_f \varepsilon_f + \dot{m}_a \varepsilon_a + \dot{m}_w \varepsilon_w\right) - \left(\dot{m}_{st} \varepsilon_{st} + \dot{m}_{bd} \varepsilon_{bd}\right) \tag{22}$$

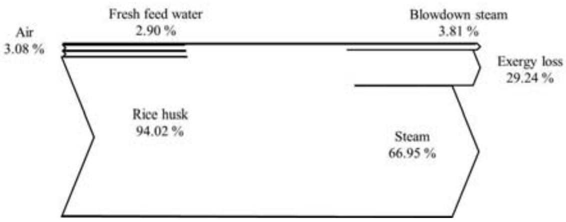
$$I_C = \dot{m}_f \left(h_f - T_0 s_f\right) + \dot{m}_a \left(h_a - T_0 s_a\right) + \dot{m}_w \left(h_w - T_0 s_w\right) - \dot{m}_{st} \left(h_{st} - T_0 s_{st}\right) - \dot{m}_{bd} \left(h_{bd} - T_0 s_{bd}\right) \tag{23}$$

The exergy efficiency of the boiler is calculated as following Eq. (7).

$\psi = 0.6998 = 69.98\%$



a) Sankey diagram for energy of boiler.



b) Sankey diagram for exergy of boiler.

Figure 4: Sankey diagram for energy and exergy of boiler.

From the calculation above, the energy and exergy efficiencies of this boiler are 72.04% and 69.98% respectively. The efficiency is not based on only the specific heat input, but it is also based on the low heating value of the fuel. Compare with the result from Saidur et al. [12], the energy efficiency of the boiler is in the same range (62 – 83% for industrial boiler). But the exergy efficiency is a bit more (40%). Figure 4 a) and b) showed the Sankey diagram for energy and exergy of the boiler system at Mahaphant Fiber-Cement Public Company Limited respectively.

3.2 *Power available diagram of the boiler*

The PAD is used to visualize for the exergy loss of the boiler system. The exergy of fuel as calculation in the previous section is changed to the exergy of the hot gas (exergy donate). The heat from hot gas is transferred to the fresh water (exergy acceptor) in the boiler [17].

The exergy loss of the boiler can be reduced by shorten the length of the exergy loss line L1 in the Figure 5. First, length L2 can be increased by increasing the temperature of the steam outlet to be superheated steam before leaving the boiler. Second, hot gas flow is control by adjusting the exhaust fan of the boiler.

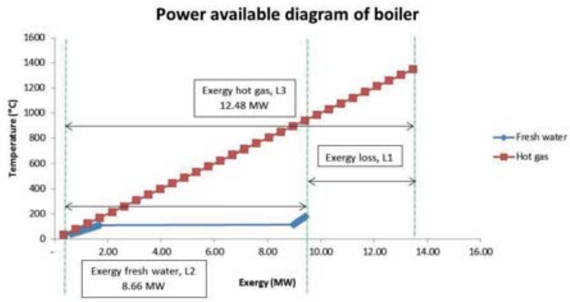


Figure 5: Power available diagram of the boiler.

It can reduce the exergy of the hot gas to the system (reduce the length of L3).

3.3 *Energy and exergy of the autoclave*

Table 3 showed the mass flow rate, enthalpy and entropy of the autoclave. The information is also collected by same methods as the boiler in the previous section. The study boundary is only one autoclave because all autoclaves are operated in the same condition.

Table 3: Mass flow rate, temperature, enthalpy and entropy of the autoclave

Substance	Mass flow rate (kg/hr.)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/ kg·°C)
Inlet				
Steam feed	13,000	180	3,116.40	0.89
Fiber cement composite	60,000	50	250.31	0.83
Autoclave shell	46,605	25	11.20	-
Steel pallets	28,000	35	16.08	0.03
Stack car	19,400	35	16.08	0.03
Outlet				
Fiber cement composite	53,571	90	452.43	1.54
Exhaust Steam	8,000	130	2,967.53	0.75
Condensate water	9,867	130	794.03	0.75
Autoclave shell	46,605	90	58.24	0.18
Steel pallets	28,000	90	47.73	0.16
Stack car	19,400	90	47.73	0.16
Heat loss		59	86.76	-

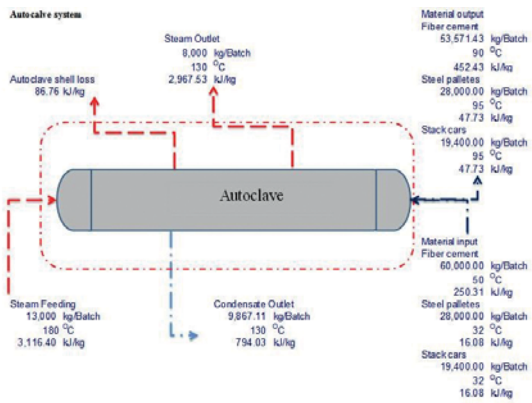


Figure 6: The overall mass and energy balance of fiber cement autoclave.

The energy input in the Table 3 can becalculated as following Eq. (18).

$$\dot{E}_{in} = \dot{m}_{fc}h_{fc} + \dot{m}_{st}h_{st} + \dot{m}_{as}h_{as} + \dot{m}_{sp}h_{sp} + \dot{m}_{sc}h_{sc} \qquad (24)$$

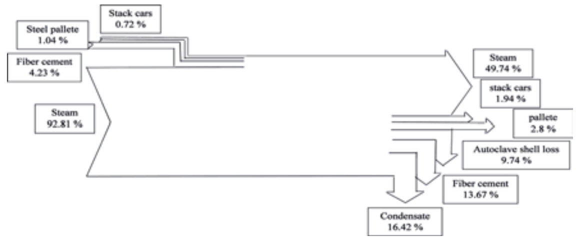
From the calculation above, the energy input to the autoclave system based on all sources of materials is equal to 43.77 GJ/batch of operation. In the output part, calculation based on the product of fiber cement product is equal to 6.53 GJ/batch. Figure 6 showed the overall mass and energy balance of the autoclave at Mahaphant Fiber-Cement Public Company Limited.

In term of the exergy analysis of the autoclave, the exergy destruction is estimated by using the Eq. (19). It is assumed that the autoclaveoperates in the steady-state process since there is no change in the process with time at any point, thus change of mass and energy of the control volume of the boiler is equal to zero. It is also assumed that there is no work interaction involved and the kinetic and potential energies are negligible. Using Eq. (19) and data from Table 3, exergy destruction has been calculated as following the equation below.

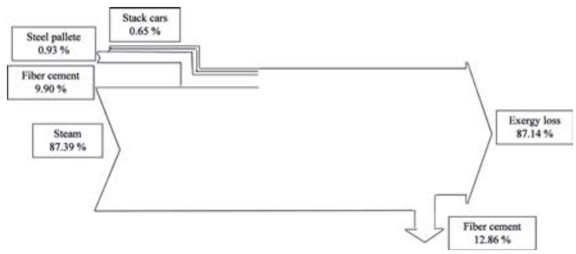
$$I_C = \left(\dot{m}_{fc}\varepsilon_{fc} + \dot{m}_{st}\varepsilon_{st} + \dot{m}_{as}\varepsilon_{as} + \dot{m}_{sp}\varepsilon_{sp} + \dot{m}_{sc}\varepsilon_{sc}\right) - \left(\dot{m}_{fc}\varepsilon_{fc} + \dot{m}_{fcm}\varepsilon_{fcm}\right) \qquad (25)$$

The calculation is showed that the exergy destructive from the autoclave system is 40.18 GJ/batch. It means that the main cause of the exergy destructive comes from the exergy of steam.

Figure 7 a) shows the Sankey diagram for the energy balance of the autoclave. The exergy of the autoclave can also be showed as Sankey diagram in



a) Sankey diagram for energy of the autoclave.



b) Sankey diagram for exergy of the autoclave.

Figure 7: Sankey diagrams for energy and exergy of autoclave.

Figure7 b). The exergy destruction is about 87.14%.

The energy and exergy analysis of the autoclave showed that the main three energy losses of the system are exhaust steam (49.74%), condensate (16.42%) and shell heat loss (9.74%). In term of the exergy analysis, the exergy destruction of the autoclave is 87.14%. It is high because the exhaust steam and condensates left the autoclave at high temperature and pressure. Both streams have high available energy that can be used. The reduction of exergy destruction can be done byutilizing more heat from steam to the product and releasing at lower temperature and pressure. This result cannot be compared with other autoclave because it is depend on the product and operation process. If the product is difference, the operation parameter and energy consumption are difference.

3.4 *Power Available Diagram of the autoclave*

The PAD of the autoclave cannot show the relation of the exergy loss from the autoclave PAD because the originally the PAD concept is an application to heat exchanger and power cycle, but main energy on this process goes through reaction on cement formation. Therefore, we cannot interpret directly from this PAD.

Therefore, this article can cover most energy usage in common fiber cement by representing those energy and exergy loss by PAD.

The implementation by adjusting process steam can result the exergy efficiency up to 60% comparing to 20% from industrial boiler studied by Saiduret et al. [12].

4 Conclusions

The analysis of energy and exergy for the boiler and the autoclave at Mahaphant Fiber-Cement Public Company Limited was done in this study. The analysis of the boiler showed that the total energy input is 13.05 MW with the boiler efficiency 72.04%. It is in the normal range of the boiler with internal heat exchanger. The main energy loss from the boiler is the exhaust gas with the energy loss about 34 %. The exergy analysis showed that this system has exergy destruction about 30% or 3.89 MW and the exergy efficiency at 69.98%. The Power available diagram is also used to evaluate the exergy loss of the boiler, and the result is 30.18%. The exergy loss reduction can be done by increasing the stream outlet temperature or reducing the temperature of the exhaust gas of the boiler. For the autoclave, energy analysis showed the total energy input about 43.67 GJ/batch. The three main energy losses are the exhaust steam (49.74% or 23.74 GJ/batch), condensate (16.42% or 7.83 GJ/batch) and autoclave shell heat loss (13.67% or 6.25 GJ/batch). For the exergy, the exergy destruction in the autoclave is about 87.14%. The main causes of the exergy destruction are according the three main energy losses. There are the exhaust steam (50.80%), condensate (16.47%) and autoclave shell loss (10.01%), respectively.

Nomenclature

$CaCO_3$	Calcium carbonate
$CaSO_4 2\cdot H_2O$	Calcium sulphate di-hydrate, Gypsum
E	Exergy [kJ/hr.]
h	Specific enthalpy [kJ/kg]
H_2O	Water
I	Exergy destruction [kJ/hr.]
ke	Specific kinetic energy [kJ/kg]
LHV	Low heating value [kJ/kg]
m	Mass [kg]
P	Pressure [kPa]
pe	Specific potential energy [kJ/kg]
Q	Heat transfer rate [kJ/hr.]
RH	Relative humidity (%)
s	Specific entropy [kJ/kg·°C]
T	Temperature [°C]
W	Work [kJ]
x	Mass fraction, Dimensionless

Greek Symbol

′	Outlet condition
ε	Specific exergy [kJ/kg]
η	Energy efficiency, Dimensionless
μ	Chemical composition
ψ	Exergy efficiency, Dimensionless

Subscript, Superscript Index Sets

0	Reference environment at 25°C, Pressure at 100 kPa
00	Equilibrium state
a	Air
ad	Air dry
am	Air moisture
as	Autoclave shell
bd	Blow down
c	Destruction
CH	Chemical exergy
f	Fuel
fc	Fiber cement
fcm	Fiber cement moisture
fd	Fuel dry
fm	Fuel moisture
gen	Generate
in	Input
j	Chemical specie
KN	Kinetic exergy
out	Output
PH	Physical exergy
PT	Potential exergy
r	System boundary
sc	Stack car
sp	Steel pallets
st	Steam
w	Water

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