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Thermodynamic Analysis of Raw Mill in Cement Industry Using Aspen Plus Simulator

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Abstract. This study investigates the appropriateness of exergy calculation using Aspen Plus Process Simulator which has a robust data library and powerful engineering calculation capabilities. The simulator was used for the thermodynamic performance of a raw mill (RM) and raw materials preparation unit in a cement plant in Nigeria using actual operating data. The raw mill has a capacity of 240,000 kilogram-material per hour. Also, both exergy and exergetic efficiency of raw mills from three literature sources were investigated and compared with the simulation results from Aspen Plus process model. The results were subjected to statistical analysis using ANOVA. The exergy efficiency for the raw mill studied using Aspen plus simulator modelling technique was found to be 21.4%. It was found that the difference in exergy efficiencies of the simulation results of the three-literature data vary within ±2.5% of the published results. The present method using the Aspen plus simulator is suggested as a useful tool in making informed decisions for developing energy policies and exergy utilization, providing energy conservation measures in improving the efficiency of the system.
Keywords: Cement Industry, Raw Mill, Exergy, Exergy Efficiency, Process Modelling and Simulation

1. Introduction

It has been asserted that the energy resources in the world are finite in nature and this consciousness has necessitated prudent utilization of energy sources [1]. Energy conversion and energy utilization processes are being closely considered to effectively utilise the limited energy resources. For economic, environmental and sustainability reasons, more attention is being paid to improvement of processes and efficient use of energy [2 -4]. The first law of thermodynamics has been applied extensively for performance evaluation of energy system. The first law of thermodynamics though helpful in certain ways, is not sufficient to handle the intricacies of energy transformation as it fails to consider entropy generations and irreversibilities associated with real processes [5].

All real processes are accompanied by a level of entropy generation leading to irreversibilities and as energy is being transformed, it gets degraded in quality even though the quantity of energy is conserved. Irreversibilities and degradation of energy reduces the quantity of energy that is available to be transformed to useful work. A measure of useful work extractable from energy sources is therefore of more importance than the quantity of the energy itself. With respect to this, exergy, a concept which stems out of the first and second laws of thermodynamics is an invaluable tool for evaluating thermodynamic performance of energy requiring and energy producing systems as it typifies the moiety of energy that can be transformed into the maximum useful work. Dissimilarly to energy, exergy is not conserved but depletes due to irreversibilties as transformations take place. In terms of useful work extracted from an energy source, performance evaluations based on exergy analysis give true efficiency of a system. In which case, the thermodynamic imperfections

arising from irreversibilities are considered to be exergy destroyed and this represents losses in energy usefulness or quality. With exergy analysis, efficiencies that truly measure how nearly actual performances tend towards the ideal are obtained and the locations, types and causes of thermodynamic losses are more clearly identified [6]. The units or areas where there are significant differences between the actual performance and the ideal performance are the potential areas where engineers and scientist target for improvements.

Methods of exergy analysis have been developed over the years and exergy related calculations require values of some thermodynamic properties [7]. Despite the vast amount of thermodynamic data available, there are few pure substances for which we have thermodynamic data in the range of temperature of interest, therefore, it is usually necessary to calculate thermodynamic properties of pure component and mixtures from basic data, correlations and equations of state. In past works, most of the data estimations and exergy calculations have been semi-automated or carried out manually. More often than not, these processes of data generation via semi-automation or manual calculation and estimations are laborious and error prone. Error in data collection will inevitably lead to erroneous and misleading exergy values thereby defeating the essence of exergy analysis. Avoiding errors due to omission and commission in exergy analysis is therefore paramount.

The cement production being a complex process combines various endothermic, exothermic reactions with heat transfer in the solid, liquid, and vapour phases of different materials. Therefore, for sustainable and more efficient processes, the use of process engineering tools, such as process modelling software is inevitable as an alternative. In this study, the peculiarity of the material and exergy balance in a cement industry makes ASPEN Plus an essential tool for the analysis. The process equipment design, simulation or modelling and sensitivity analysis utilized ASPEN Plus as a process simulator. One of the key features of Aspen Plus software is the availability of large numbers of the physical, chemical and thermodynamic property data, which enables modelling of most of the complex industrial processes. This study investigates the appropriateness of using Aspen Plus process simulator in thermodynamic analysis of raw mill in cement industry. A local raw mill in Nigeria and three others from literature were analysed.

2. Theoretical Analysis of Mass, Energy and Exergy

The work and heat interactions, including rate of exergy decrease, irreversibility, energy and exergy efficiency are required at steady state.

2.1 Mass balance

The mass balance equation at steady state can be written in the rate form as
$$\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out} \tag{1}$$
Where, $\dot{m}$ is the mass flow rate for both inlet and outlet.

2.2 Energy balance

The general energy balance can be expressed as
$$\Sigma E_{in} = \Sigma E_{out} \tag{2}$$
$$Q_{net\ in} + \Sigma \dot{m}_{in} h_{in} = W_{net\ in} + \Sigma \dot{m}_{out} h_{out} \tag{3}$$
Where, ΣE_{in} is the total sum of the energy transferred in, ΣE_{out} is the total sum of the energy transferred out. It is assumed that $Q_{net\ in} = 0$ and $W_{net\ in} = 0$. Then, Equation (3) reduces to:
$$\Sigma \dot{m}_{in} h_{in} = \Sigma \dot{m}_{out} h_{out} \tag{4}$$

2.3 Exergy balance
Assuming that other parameters are negligible, then total exergy of a system are evaluated using both physical exergy, ($\dot{E}x_{phy}$), and chemical exergy, $\dot{E}x_{ch}$

The physical exergy can be stated as:
$$\dot{E}x_{phy} = (h - h_0) - T_0(s - s_0) \tag{5}$$
While the chemical exergy of the ideal gas with liquid mixtures is calculated from:
$$\dot{E}x_{ch} = \Sigma x_i((\dot{E}x_{choi}) + RT_0(In\ x_i)) \tag{6}$$
Where x_i represent the species i molar ratio, and $\dot{E}x_{choi}$ also represents the standardized chemical exergy.
Exergetic performance is expressed as:
$$\in 1 = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \tag{7}$$
Anergy, Φ, is expressed as:
$$\Phi = \frac{\dot{E}x_{losses}}{\dot{E}x_{input}} \tag{8}$$
The irreversibility of the system is expressed as:
$$I_{sys} = \dot{E}x_{input} - \dot{E}x_{output} = T_o S_{gen} \tag{9}$$
Where, I_{sys} is known as exergy destroyed or irreversibility and S_{gen} is the entropy generated.

3. Cement Production Process

Cement industry is usually located very close to the deposit of a naturally occurring rock material such as limestone or chalk or calcium carbonate ($CaCO_3$), which provides a major constituent when extracted from quarries. Iron ore (Fe_2O_3), bauxite (Al_2O_3) , shale, clay, slag or sand (SiO_2) are considered as minor materials which may be needed in very small quantity to provide the extra mineral ingredients for cement production. The mined material is conveyed with the aid of dump truck to primary and secondary crushers and reduced into less than 10 centimetre pieces.

The crushed raw materials are mixed and stored for homogenization purpose, then milled together using raw mill (ball or vertical) to produce 'raw meal' under a strict quality control of the material chemistry. Hot flue gases coming from the rotary kiln, which is in the opposite direction with the material flow, preheat the powdered raw meal at the preheater tower before it finally enters the kiln. In these preheater cyclones, raw meal is preheated with heat exchange taking place to improve the process efficiency and less fuel consumption. The raw material moisture content and heat recovery efficiency determines the investment type of a rotary kiln and stages of cyclone required. The additional fuel introduced at the calciner, is partly used to increase the raw meal temperature to calcining level and primarily to implement actual calcination process (decomposition of limestone into lime CaO and CO_2).

Precalcined meal enters the rotary kiln at temperatures of approximately 1050°C. The rotary kiln is being fired directly or indirectly to a temperature above 1800°C to ensure a well prepared material. The raw material flows down the kiln due to an inclined positioning, to the burning zone, the hottest region of the kiln. Both chemical and physical reactions occur as a result of an intense heat which partially melts the meal into clinker. From the kiln, the hot clinker is moved to the grate cooler where it is cooled to a temperature between 85°C to 120°C with cooling fans, part of which is used as combustion air.
The clinker formed is mixed with 4-5% gypsum, with small quantity of limestone or slag (filler). All these are milled into a final product called cement, or Portland Composite Cements depending on the type and quantity of fillers added.

3.1 Raw materials Preparation

The raw meal preparation flowsheet is shown in Figure 1. The most common and vast raw materials is limestone ($CaCO_3$) of varied quality, in addition with much smaller quantities of clay, shale and sand (as a source of silica, aluminum and iron). A common belt conveyor transfers the different raw material components from the weigh feeders directly to the mill inlet. The grinding rollers are forced downwards onto the materials.
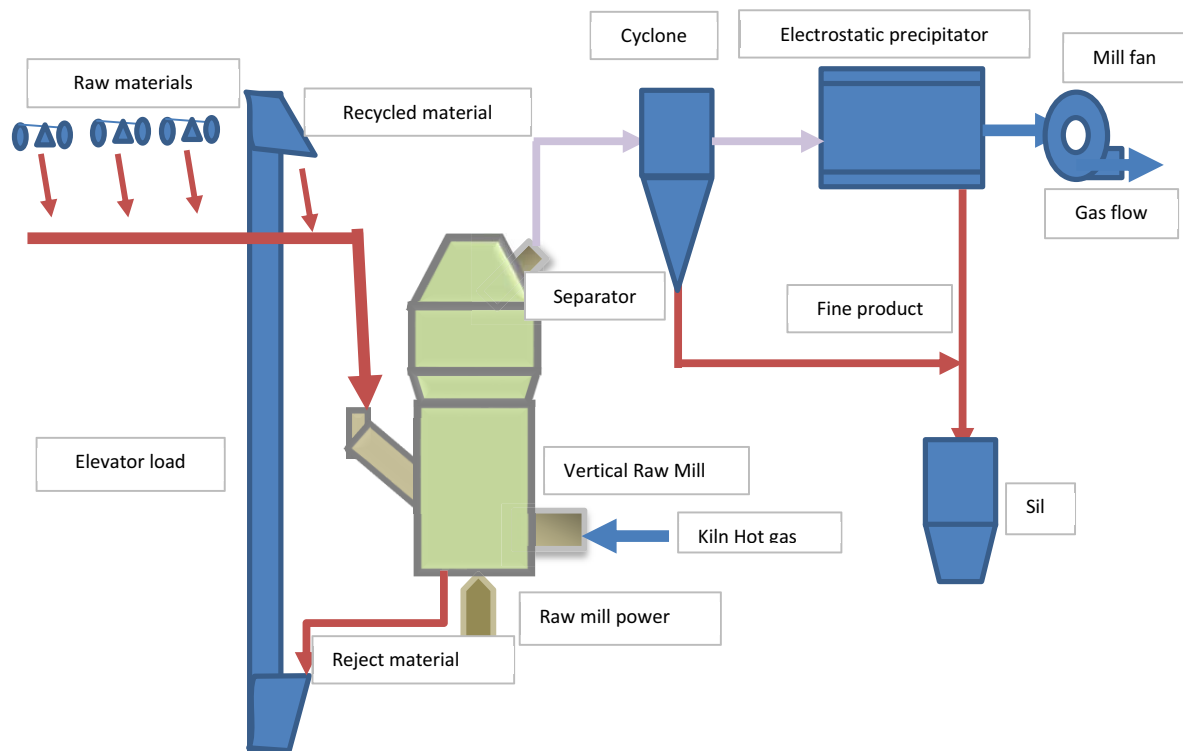
Figure 1.   Raw Meal Preparation Flowsheet

As the material is ground by the rollers, it continues to move to the periphery of the grinding table. As the material spills over the dam ring, it is suspended in the air stream by the hot gases from the kiln or preheater. The hot gases enter the base of the mill and pass upwards through a louvered annular ring around the grinding table. The entrained fine material is carried by the air stream upwards into the classifier forming the upper part of the mill. The fine particles pass the separator and leave the mill as final product. The coarser particles will be rejected by the separator and recycled to the grinding table for further grinding.

The major part of the fine material leaving the mill separator with the outgoing gases is precipitated in cyclones. This material is conveyed to the blending storage silo for raw meal. The remaining fine dust from the mill not precipitated in the cyclones is carried to the electrostatic precipitator, where the fine cleaning of the gases takes place, before the gases (now cleaned) are sent into the atmosphere by the filter fan. The raw meal is a milled fine powder from the proportioned raw materials with correct chemical balance. To ensure consistency in product quality, homogenization of material is essential. The production rate of the raw mill is 240,000 kilogram per hour.

4. Process Simulation Model of Raw Mill

The raw mill as a unit operation in cement manufacturing process was simulated using Aspen Plus version 8.4. "SOLID Model" inbuilt template in Aspen plus was used as a basis for the simulation model. Selection of an appropriate property package which accurately reproduces the various physical properties for the system in question is a key requirement of process modelling. Redlich-Kwong equation of state method is being used

to find the vapour phase properties, while Henry's Law handles the supercritical components present in the liquid phase using asymmetric convention. The equilibrium constants and enthalpy are solved using Kent-Eisenberg method. All simulations are performed in steady state.

Modelling of solids anywhere in a process sheet has been made easy using Aspen Plus. A wide range of unit operation models for solids handling equipment is available and this includes crushers (mills), screens (separator), cyclones and electrostatic precipitator. Material and energy streams are represented using blocks which are placed on a flowsheet. An extensively built-in databank of both physical and chemical properties was used for the simulation calculations. Properties and component flows of different types such as liquid, solid and vapour are reported in 'Solids Template'. Mixed conventional solids with particle size distribution (MIXCIPSD) is present. The following assumptions were made in the development of the models:

a) The process operates in steady state conditions and ignores pressure losses, turbulent motions, and air leakages.
b) Both the atmospheric and pressure drop of the process is considered negligible.
c) No heat losses through the system
ASPEN Plus model could be developed through these processes:

• Property selection method and stream classes ae described.

• Comprehensive databank for system component description.

• Process flow sheet are defined base on the unit operation of blocks with the connecting material and energy stream. This also involves the thermodynamic conditions with both the physical and chemical reactions in the blocks.

• Feed stream description, which includes mass or volumetric flowrate, feed component, with particle size distribution.

The process model is based on a raw mill plant operation with capacity of 240,000 kg per hour, and includes the required physical property parameters to simulate this type of system. The raw mill process consists of three-unit operations, namely: drying, grinding and separation. The raw materials were crushed/ milled and the entrained fine material is carried by the air stream upwards into the classifier forming the upper part of the mill. The rich inlet stream is defined as "Solid-Liquid" and "Solid-Vapour", meaning that it is treated as a two-phase stream by Aspen Plus. The stream leaving the mill is led into a screen (separator), where the fine dust is separated from the course and the coarse recycled back to the mill for regrinding. The mixed fine dust (product) and gas is transported to cyclones where the fine dust in gas stream is separated and stored in the silo as kiln feed. The gas stream laden with dust is led to the electrostatic precipitator to trap the fine dust while the cleaned gas leaves to the environment.

Crusher (mill)

Crusher (mill) model is a dry grinding continuous operation that assumes homogeneity of inlet feed. The raw material is crushed/milled and the entrained fine material is carried by the air stream upwards into the classifier forming the upper part of the mill. Both the feed stream and the outlet particle stream are of the same composition, and no chemical reaction takes place. The operation only involves size reduction to fine particles.

Screen (Separator)

The stream leaving the mill is led into a screen (separator), where the fine dust are separated from the coarse and the coarse recycled back to the mill for regrinding. The simulation of the screen (separator) sizes of entrained fine material will determine the quantity recycled or allow passing as final product and this depict the separation efficiency of the screen.

Cyclone

Further separation of gas laden with dust is simulated with cyclone separators. The fine dust particles is removed from a dust entrained gas stream with the aid of a centrifugal force of a gas vortex obtained from cyclone.

Electrostatic precipitator (ESP)

Final separation of the gas stream entrained with dust particles is done using electrostatic precipitator before the clean air is released to the atmosphere. ESP, as Electrostatic precipitator is used for the simulation. Positioning of the wires in parallel and in between the plates makes it easy for the electrostatic field of the collecting plate electrodes to remove the dust particles from the gas stream.

4.1 Simulation Data

The main purpose of the raw mill plant simulation is to make a simple but realistic model to evaluate the exergy efficiency of the overall raw mill plant. The raw mill with a capacity of 240,000 kilogram-material per hour has been simulated with Aspen Plus. The chosen property package for the simulations performed in this paper was the "SOLID", however, in order to cater for the thermodynamic requirements of the two phase streams, the components are distributed over the sub-stream of types MIXED and CISOLID as this is the most accurate property method for the simulated processes.

Specifications for the calculation in ASPEN PLUS Simulation are listed in Tables 1 to 4. The flowsheet of the Aspen Plus process model for raw meal preparation is presented in Figure 2.

Table 1: Specification for Raw mill simulation

	Unit	
Inlet material flow	kg/h	240,000
Inlet moisture flow	kg/h	48,000
Inlet hot gas flow	kg/h	477,086
Inlet dust flow	kg/h	19.353
Inlet hot gas temperature	°C	290
Inlet material temperature	°C	30
Operating Pressure	atm	1
Cyclone efficiency	%	96
Separator efficiency	%	86
Electro-static precipitator efficiency	%	84

Table 2: Typical composition of Raw Material

Component	Weight Percentage (%)
CaCO3	75
SiO2	22
Al2O3	2
Fe2O3	1

Table 3: Material Particle size distribution for raw mill inlet

Sieve size	Unit	Weight fraction (%)
20	*mm*	10
40	*mm*	25
60	*mm*	30
80	*mm*	30
100	*mm*	5
120	*mm*	0

Table 4: Sieve Analysis for raw mill outlet

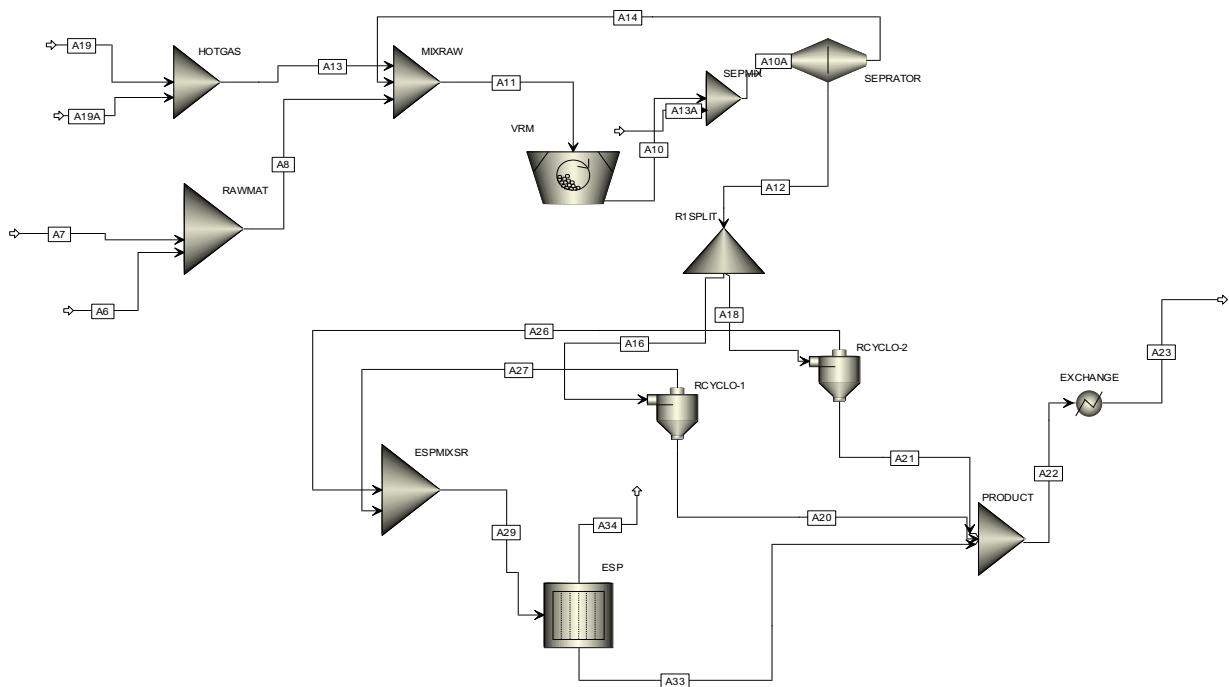| Sieve size	Unit	Weight fraction (%)
20	Mm	80
40	mm	15
60	mm	5
80	mm	0

Figure 2:   Aspen Plus process model flowsheet for raw meal preparation

4.2 Material and Exergy Balance Calculations

The raw mill mass balance is a representation of the law of conservation of mass of Eq. (1), which on application on the raw mill becomes:

$$\Sigma\dot{m}_{in} = \dot{m}_{raw\ feed} + \dot{m}_{hot\ gas} + \dot{m}_{moisture} + \dot{m}_{return\ separator} + \dot{m}_{dust\ in\ hot\ gas} \qquad (10)$$

$$\Sigma\dot{m}_{out} = \dot{m}_{raw\ meal} + \dot{m}_{gas} + \dot{m}_{moisture} + \dot{m}_{steam} \qquad (11)$$

The feed stream for each component is supplied with other necessary parameter for each block and the software in turn generates for the outlet mass balance. ASPEN Plus calculates for each of the stream components the exergy value. Exergy efficiency of the raw mill can be calculated using equation (7).

5. Results and Discussion

The results of the raw mill thermodynamics analysis with Aspen Plus process simulation model using available data from a local cement plant and three literature data are presented in this section.

5.1 Local raw mill simulation and exergy analysis

The Aspen Plus process simulation results of material balances of the local raw mill are presented in Table 5.

Table 5: Simulation results for the Mass balance of the local raw mill

Mass Balance of Raw mill							
Input				Output			
Material	Unit	Plant data	Simulation	Material	Unit	Plant data	Simulation
Raw feed	kg/h	240000	240000	Raw meal	kg/h	235300	231977
Moisture in raw feed	kg/h	48000	48000	Gas	kg/h	555260	558487
Hot gas from kiln	kg/h	477086	477086	moisture	kg/h	3266	3564
Dust in hot gas	kg/h	19353	19353	Steam	kg/h	65612	65412
Return from separator	kg/h	75000	75000				
Total		859439	859439	Total		859439	859439

It was observed that the input of the material simulation results is the same as that of the actual plant data and that the output of the material simulation results varied though not excessively with the actual plant data since at significance level set at 0.05, the calculated *F* value (8.14E-12) was less than *Fcritical* (5.987378). This is an indication that the software can simulate the material balance of the raw mill in cement industry within acceptable limits of accuracy. The results of the exergy balance for the local raw mill are shown in Table 6.

Table 6: Simulation result for the exergy balance of the raw mill

Exergy balance of raw mill					
Input			Output		
Material	Unit	Simulation	Material	Unit	Simulation
Raw feed	kJ/h	3194	Raw meal	kJ/h	2024720
Moisture in raw feed	kJ/h	-9053	Gas	kJ/h	7545475
Hot gas from kiln	kJ/h	47474430	moisture	kJ/h	48152

Dust in hot gas	kJ/h	1655660	Steam	kJ/h	926255
Return from separator	kJ/h	173780			
Total input Exergy		49298012	Total output Exergy		10544602
Exergy efficiency		21.4%			

The exergy efficiency of the local raw mill is 21.4%. It was found from Table 6 that at the operating conditions, exergy loss is (38753410 **kJ/h**) and this corresponds to 78% of the total exergy input to the raw mill. The exergy and mass flow diagram of the local raw mill is presented in Figure 3 and shows that most of the exergy input to the system was due to hot gas and dust (96.6%) followed by the returned material (3.3%) with the exergy of raw materials contributing less than 1%.
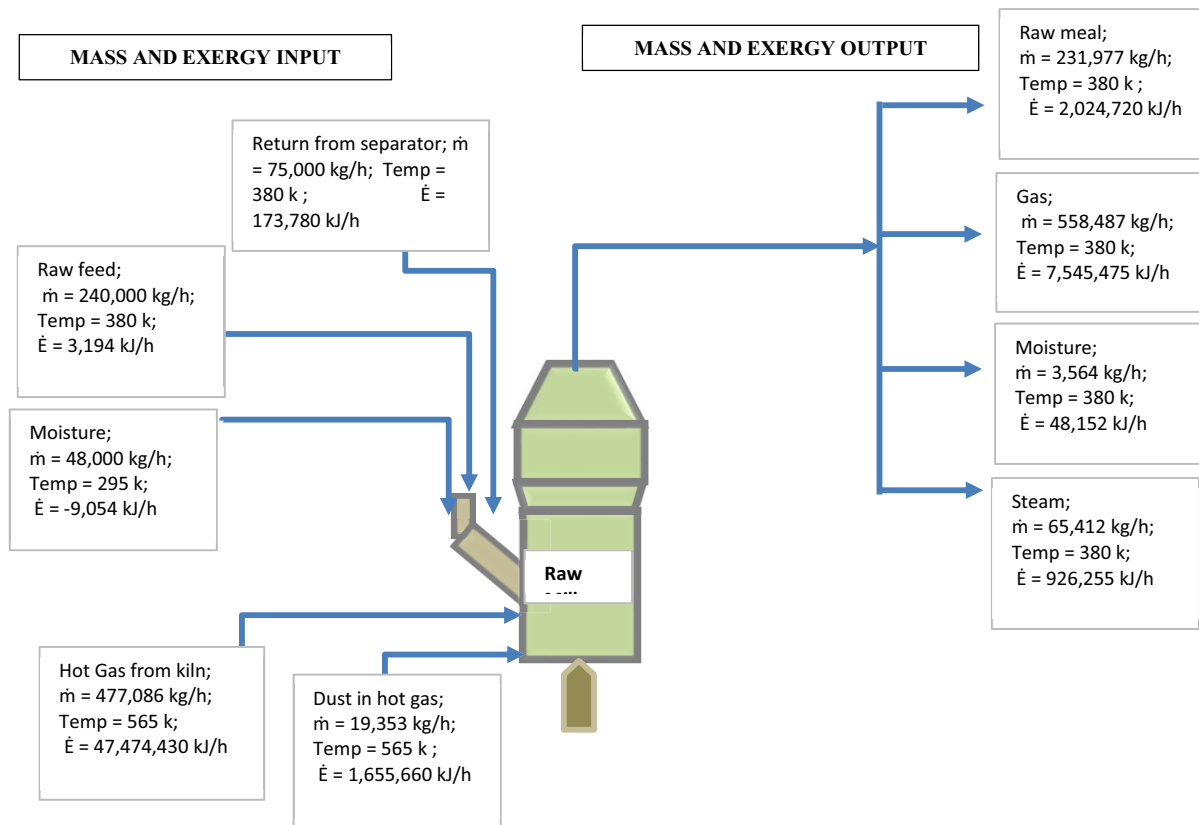

Figure 3.   Exergy and mass flow diagram of the raw mill

5.2 Simulation and exergy analysis of raw mills from literature

The Aspen Plus process simulation results of material balances of three raw mills from literature, namely: Utlu et al. [8], Dyuthi [9] and Atmaca et al. [10] are presented in Table 7.

Table 7: Comparison of simulation results and literature values of the mass balance of raw mill

Mass balance of the raw mill from the literature

		Utlu et al. [8]		Dyuthi [9]		Atmaca et al. [10]	
Input	Unit	Literature data	Simulation	Literature data	Simulation	Literature data	Simulation
Raw feed	kg/h	82515	82515	117352	117352	135016	135016
Moisture in raw feed	kg/h	6065	6065	3696	3696	15038	15038
Hot gas from kiln	kg/h	49464	49464	98714	98714	66346	66346
Dust in hot gas	kg/h	3067	3067	3043	3043	2103	2103
Return from separator	kg/h	36000	35999	242000	242143	27104	27218
Total		177111	177110	464805	464948	245607	245721

		Utlu et al. [8]		Dyuthi [9]		Atmaca et al. [10]	
Output	Unit	Literature data	Simulation	Literature data	Simulation	Literature data	Simulation
Raw meal	kg/h	121582	120853	362395	362499	162223	162076
Gas	kg/h	49464	51559	98714	98161	68346	68592
Moisture	kg/h	715	475	605	513	6430	6435
Steam	kg/h	5350	4223	3091	3775	8608	8618
Total		177111	177110	464805	464948	245607	245721

It was observed that the input of the material simulation results are the same as that of the literature data except for the return from separator stream which varied very slightly with literature data; and that the output of the material simulation results varied though not excessively with literature data. The same trend was observed for the material simulation results for the local raw mill and the raw mills from literature data. The results of exergy balance of the raw mills from literature and simulation using Aspen Plus process simulator are shown in Table 8.

Table 8: Comparison of simulation results and literature values of the exergy balance of the raw mill

		Utlu et al. [8]		Dyuthi [9]		Atmaca et al. [10]	
Input	Unit	Literature data	Simulation	Literature data	Simulation	Literature data	Simulation

Raw feed	kJ/h	-1041	1140	3724	1758	4428	4
Moisture(feed)	kJ/h	-381	2929	641	10397	2664	11315
Hot gas from kiln	kJ/h	7405586	7897690	11912266	13099390	7950060	9614140
Dust in hot gas	kJ/h	310257	267223	338809	36031	180144	147835
Return from separator	kJ/h	150310	299892	831427	312559	160164	242785
Total input exergy		7864732	8468874	13086866	13460135	8297460	10016079

		Utlu et al. [8]		Dyuthi [9]		Atmaca et al. [10]	
Output	Unit	Literature data	Simulation	Literature data	Simulation	Literature data	Simulation
Raw meal	kJ/h	1087322	1006770	1744570	1954000	1733616	1445710
Gas	kJ/h	758158	810269	562588	438187	1151136	1840790
Moisture	kJ/h	29475	84671	14843	13983	350856	355597
Steam	kJ/h	106453	138715	35467	64414	47592	369549
Total output Exergy		1981408	2040426	2357467	2470584	3283200	4011646
Exergy efficiency		25.2%	24.1%	18.0%	18.4%	39.6%	40.1%

It was observed that the exergies of the streams in literature data and simulation varied. The differences in exergy of streams are due to the differences in the datum levels used in calculation of thermodynamic data in the literature data and Aspen Plus process simulator. The exergy efficiencies of the raw mills from literature were calculated with the electrical work included in the exergy input. The exergy of electrical work is excluded in this work so as to focus on the suitability of using Aspen Plus process simulator to evaluate the exergy efficiency of the raw mills based on exergy of material streams and make a comparison between exergy efficiencies from literature and this work. As shown in Table 8, average deviations of exergy efficiencies for the literature data and simulation vary within ±2.5% for the three individual literature data. The Aspen Plus simulation model can therefore be considered as a reliable and efficient tool to predict the exergy of material streams and exergetic efficiency of raw mill operation.

6. Conclusion

This study focused on exergy utilization, exergy balance and irreversibility for a raw mill in the cement industry using the real plant data and literature data. Exergy efficiency of the raw mill studied using Aspen plus simulator modelling technique was found to be 21.4%. It was found that the simulation results of the three literature data vary within ±2.5% of the published results. From the operating conditions, the raw mill exergy efficiency is very poor. The study is limited only to the material streams exergy of the system

investigated. The present method using the Aspen plus simulator is suggested as a useful tool in making informed decisions for developing energy policies.

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