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Energy Auditing and Waste Heat Recovery for Dry Type Cement Kiln System in Ethiopia: A Case Study

Beniam Getasetegn Emyat

Department of Mechanical Engineering, School of Mechanical and Industrial Engineering, Institute of Technology, University of Gondar, P.O. Box: 196, Gondar, Ethiopia

E-mail: diyakonbenget27@gmail.com

Abstract*:* The aim of this study is energy audit and heat recovery of a dry type technology of cement industry in Ethiopia. The kiln has a capacity to produce 2000 ton-clinker per day. By considering 12 months data for mass and energy balance, auditing energy is performed. From the result about 35% of the total input energy was being lost through hot flue gas (19.53%) and cooler stack (16.22%). By using waste heat recovery steam generator (WHRSG) about 5 MW (6.13%) of the total input energy could be recovered. The whole electrical energy usage of the kiln system safely used from the generated power. So, the factory could keep 800,000 USD/Year by using the generated power for production of clinker.

Keywords: Cement plant; Kiln system; Energy audit; Waste heat recovery

INTRODUCTION

Cement production is an energy intensive process, consuming about 4 GJ per ton of cement product. In order to produce one ton of clinker a minimum of 1.6 GJ heat is required [Liu et al., 1995]. However, now days, it is about averagely 2.95 GJ energy is consumed per ton of cement for advanced kilns, but in some countries, the consumption exceeds 5 GJ/ton. For example, the average energy requirement of Chinese key plants to produce clinker is 5.4 GJ/ton [Khurana et al., 2002]. The energy audit is the most effective procedures for good and well energy management program [Pahuja, 1996]. The main goal of energy audits is to give a correct account of energy requirement and use analysis of different components and to provide the detailed information needed for determining the possible opportunities for energy conservation. There are technical ways to improve overall kiln efficiency like waste heat recovery from hot gases and hot kiln surfaces [Pahuja, 1996 and Kamal, 1997]. However, it is difficult to express a detailed thermal analysis of rotary kiln systems in the cement plant.

The main objective of this study is about the energy audit and ways of heat recovery mechanism of the kiln system, by using WHRSG and also giving directions on how to increase the efficiency of the system and reduction of energy consumption on Messebo Cement Plant line-1 in Ethiopia. First energy auditing is performed and then, application of WHRSG for heat recovery mechanisms are discussed.

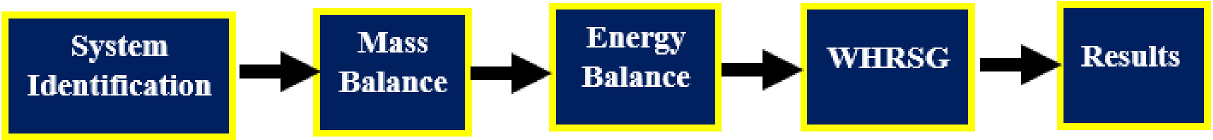

Figure 1. Methods for waste heat recovery mechanism

PLANT AND PROCESS DESCRIPTION AND DATA GATHERING

The cement plant in this paper is one of the major cement producing industry in Ethiopia. The plant is installed at an altitude of about 2200 meters above sea level [Bayray et al., 2013]. The plant produces 2,000 tons/day and uses dry type technology with five stage cyclone preheaters and pre-calciner kilns and grate cooler. The rotary kiln has 3.8m diameter and 57 m length. Specifically energy consumption of the plant is 3.7 GJ per ton of clinker and the average coal consumption of the kiln system for 12 months is 230 tons/day. The system of the cement production mainly includes following steps:

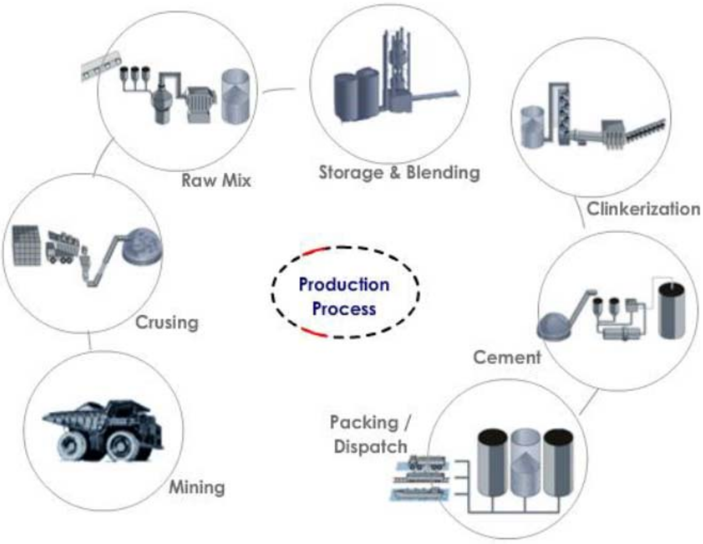

Figure 2. The production process of cement.

From Messebo Cement Plant line 1 large number of data have been collected for a long time and different measurements are used in 12 months and averaged and interpolated values are used in this study.

ENERGY AUDITING AND HEAT RECOVERY

3.1 Assumptions

The following assumptions are made to analyze for auditing energy.

a) The system is steady state and steady flow.

b) Ambient temperature are constant throughout the study i.e. T0 = 297K.

c) The composition of raw material and coal material and feed rate of both are constant.

e) The velocity of atmospheric air is < 3 m/s.

f) The temperature of kiln shell is constant throughout the study.

g) Consider the gases inside the kiln as an ideal gas.

3.2 Mass Balance

It is usual to define mass/energy data per kg clinker production per unit time.

Table1. Raw materials and clinker mixtures and their amount in percent

Mixtures	Raw Materials (%)(kg/kg)	Clinkers (%)(kg/kg)
SiO_2	13.4	21.1
Al_2O_3	3.2	4.08
Fe_2O_3	2.4	4.01
CaO	42.35	66.44
MgO	1.71	2.42
SO_3	0.4	1.15
K_2O	0.27	0.5
Na_2O	0.09	0.3
H_2O	0.01	---
Organics	0.8	---
Ignition loss	35.4	---
Overall	100%	100%

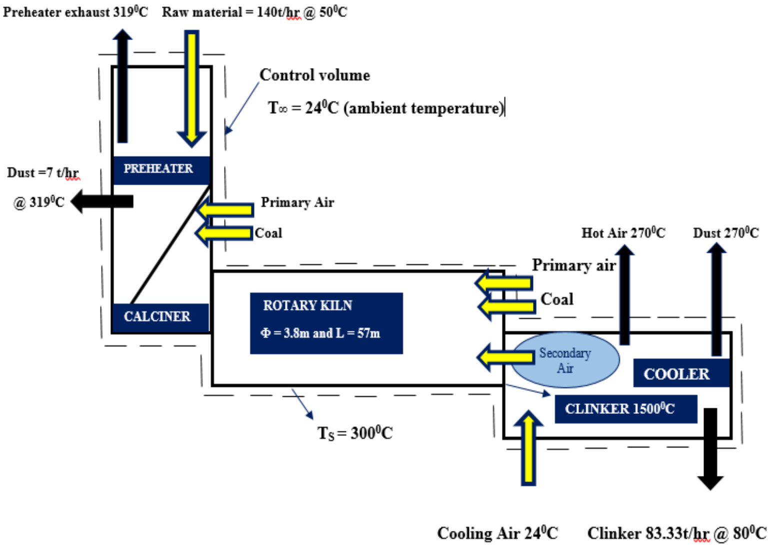

Figure 3. Control volume, various streams and components for kiln system.

Energy Balance

Based on the collected data, the energy balance is applied to the kiln system. By using Zur-Strassen equation the energy used for clinker formation can be found [Peray, 1979 and Tahsin, 2004].

Clinker formation energy = 17.196(Al2O3) + 27.112(MgO) + 32(CaO) - 21.405(SiO2) - 2.468(Fe2O3)

By using Dulong's formula the GCV (Gross Calorific Value) of the coal is found [R.K. Patil et al., 2013].

GCV = 337 x C + 1442 (H – O/8) + 93 x S

Table2. Percentage composition of Coal

Element Content	Percentage (%)
C	73
H	3.5
O	6
N	1.75
S	1.59
Ash	3.01
Moisture	0.309
Volatile	4.67
Fixed Carbon	9.05

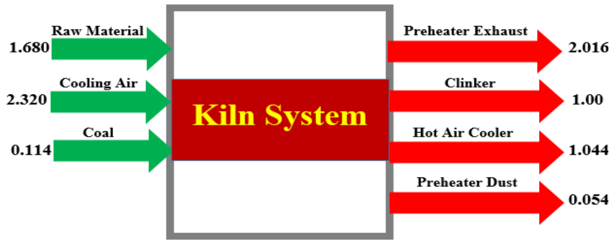

Figure 4. Mass balance of the kiln system.

Heat Inputs

1. Combustion of Coal (95.22%)

   $Q_1 = M_c\ H_c = 3358.25$ kJ/kg-clinker
   M_c=0.114kg/kg-clinker
   H_c=29,458.32kJ/kg
2. Sensible heat by coal (0.19 %)

   $Q_2 = M_c\ H_c = 6.9$ KJ /kg-clinker, H_c = CT C=1.15kJ/kg^{0}C T=50^{0}C
3. Heat by Raw material (2.05%)

   $Q_3 = M_{Rm}H_{Rm} = 72.24$ kJ /kg-clinker, H_{Rm}= CT C=0.86kJ/kg^{0}C T=50^{0}C
4. Organics in the kiln feed (0.54%)

   $Q_4 = BSh_{or} = 18.93$ kJ /kg-clinker, B=0.10, S=0.009, h_{os} =21,036 kJ/kg
5. Heat due to cooling air (2%)

   $Q_5 = M_{ca}H_{ca} = 70.5$ kJ /kg-clinker, H_{ca} = 30 kJ/kg
6. Total heat inputs

   $Q_T = {}_{i=1}\sum^{5} Q_i$= 3526.82kJ/kg (100%)

Heat Outputs

1. Kiln exhaust gas (19.53%)

   $Q_6 = M_{ex}C_{ex}T_{ex}$ = 688.76kj/kg-clinker
   C_{ex} =1.071 kJ/kg^{0}C, T =319^{0}C
2. Heat loss by dust (0.42%)

   $Q_7 = M_D h_D$ = 14.85kj/kg-clinker h_D = 275 kJ/kg
3. Hot air from cooler (16.22%)

   $Q_8 = M_{Ha}h_{Ha}$ = 571.87kj/kg-clinker h_{Ha}=547.77kJ/kg (@T=270^{0}C)
4. Clinker discharge (2.02%)

   $Q_9 = M_{clinker}\ h_{clinker@80^0C}$ = 71.09kj/kg-clinker
5. Clinker formation (51.04%)

   Q_{10}=1800kj/kg-clinker
6. The combined effects of convection and radiation on the kiln shell is calculated below and has the heat lost from kiln surface (5.27%)

Kiln surface radiation

Q = σƐA (TS4 - T∞4) /1000*MClinker =130kj/kg-clinker; TS=3000C, T∞=2400C

Mclinker=83333.33kg/3600sec =23.15kg/sec; Akiln=πDL=π*3.8*57=680.5m2

Kiln surface convection

$Q = hA\ (T_S - T\infty)/1000*MClinker$ =55.93kj/kg-clinker

hcon= Kair*Nu /Dkiln

Re=375,617.8 (Vair =3 m/s), Nu =738 T_f =162^{0}C (film temp.) [Cengel, 2003]

Hence; Q_{11} = 4.3MW = 185.94 kj/kg-clinker

7. Heat exhaust from pre-heater surface due to radiation (0.23%)

   $Q_{12} = \sigma \varepsilon A_{ph}\ (T_s{}^4 - T\infty^4)\ /1000M_{clinker}$ = 8.11kj/kg-clinker
   A_{ph} =264m^2, T_{PHs} =393K, T_∞=297K,
8. Heat exhaust from pre-heater surface due to natural convection (0.3%)

   $Q_{13} = h_{ncon}A_{ph}\ (T_s - T\infty)/1000M_{clinker}$ = 10.61kj/kg-clinker
   $h_{ncon} = K_{air}*Nu\ /L_{ph}$; Ra=5.35*10^{13},
   Nu=0.1(Ra)$^{1/3}$ Nu=3768.06 (Ref. [10]), T_f =72^{0}C (film temp.)
9. Heat exhaust from cooler surface due to radiation (0.11%)

   $Q_{14} = \sigma \varepsilon A_c\ (T_s{}^4 - T\infty^4)\ /1000M_{clinker}$=3.8kj/kg-clinker
   A_C=144m^2, T_{Cs} =383K, T_∞=297K,
   $M_{clinker}$ =23.15kg/s
10. Natural convection from cooler surface (0.07%)

$Q_{15}=h_{ncon}A_c\,(T_s - T\infty)/1000M_{clinker}$ = 2.6kj/kg-clinker

$h_{ncon}=K_{air}*Nu\,/L_C$, $Ra=7.89*10^{12}$, $Nu=0.1(Ra)^{1/3}$ Nu=1991, $L_C=12$, $T_f=67^0C$ (film temp.)

11. Moisture in raw material and coal (0.69%)

    $Q_{16}=m_{water}(h_{fg@50^0C} + h_{g@319^0C} - h_{g@50^0C})$=24.41kj/kg-clinker

    $h_{fg@50^0C}$=2384kj/kg, $h_{g@50^0C}$=2591kj/kg, $h_{g@319^0C}$=2700kj/kg, m_{water}= 0.0098kg/kg-clinker
12. Unaccounted heat losses (4.1%)

    Q_{17}=144.78kj/kg-clinker
13. Total heat output

    $Q_T=\sum_{i=1}^{17}Q_i$=3526.82kj/kg-clinker (100%)

HEAT RECOVERY FROM THE KILN SYSTEM

The overall system efficiency is given by η=(clinker formation)/(total heat input) = 1800/3526.82= 0.5104 or 51.04% which is consider as low since some kiln systems use the current technology that have 55% efficiency. In order to increase the performance of the kiln system some of the heat losses should be recovered. The recovered heat energy is used for various services, like boiling of hot water as well as electricity generation. There are two major heat loss sources that should be recovered by using WHRSG. These are preheater exhaust gas (19.53%) and hot air from cooler vent (16.22%).

Design of Waste Heat Recovery Steam Generator (WHRSG)

Based on these two highest waste heat sources, our waste heat recovery system is designed The main tapping spots are the exhaust pipe before it enters into the induced draught fan and after the first cyclone from the top for the kiln exhaust and the pipe just after the hot air leaves the cooler stack and before it goes the heat exchanger and bag filter for the cooler side. The exhaust gas from the preheater is used to dry the raw material and coal before milling. Therefore, the acid dew point temperature of preheater gases, should not be less than 1600C (The acid dew point is the temperature at which the vapor condenses and for coal range it is about 1600C) [Weston, 1992].

The exhaust gas from the preheater is 3190C and the temperature of the air exhausted from the cooler stack is 2700C. These two streams would be going through a waste heat recovery steam generator (WHRSG), and the available heat energy is transferred to water via the WHRSG as shown in Fig. 3. The available waste energy could generate steam. This steam is used to run a steam turbine to drive electrical generator. The generated electricity could cover the electrical consumption of the kiln system.

The available energy from the gas streams have to be determined, to determine the size of the generator by calculating the steaming rate and pressure. Hence, it is given by:

$$\mathbf{Q_{WHRSG} = \eta Q_{Available}}$$

The available energy that can be harnessed from the preheater exhaust gas and cooler vent hot air is given by:

$$\dot{Q}\text{available} = \dot{Q}\text{ph ex} + \dot{Q}\text{air}$$

$$\dot{Q}\text{available} = [\text{m ph ex (h ph ex1} - \text{h ph ex2}) + \text{mair (hair1-hair2)}]\dot{m}\text{clinker} = 12{,}720\text{KW}$$

Where $hair1@T=270^0C$ = 277 kJ/kg, $hair2@T=80^0C$ = 79.53 kJ/kg, h ph ex1@319⁰C =341.65kJ/kg and h ph ex2@160⁰C=171.36kJ/kg [NSRDS, 1971].

Consider the overall efficiency of the system is 90% of the total available heat. Hence, $\dot{Q}$avialable =11,450kW. This high amount of energy can be recovered but it depends on technological advancement of the system or other physical, technical and operational factors.

In order to utilize this energy, we have to select the size of the steam turbine generator. A steam turbine is a rotating machine used to produce net amount of work done. Hence, proper maintenance and clean dry steam is needed, for good operation.

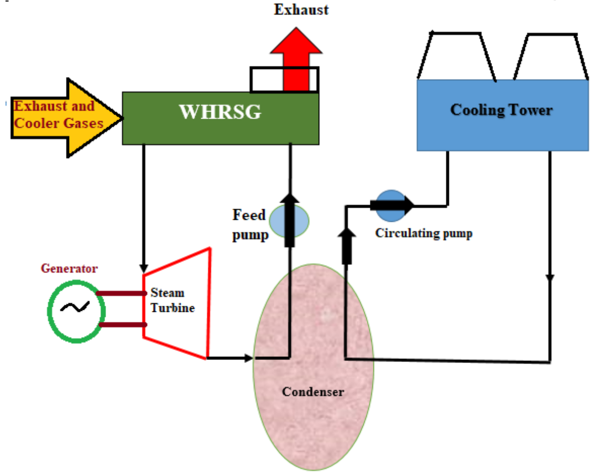

Figure 5. The use waste heat recovery steam generator (WHRSG) process diagram.

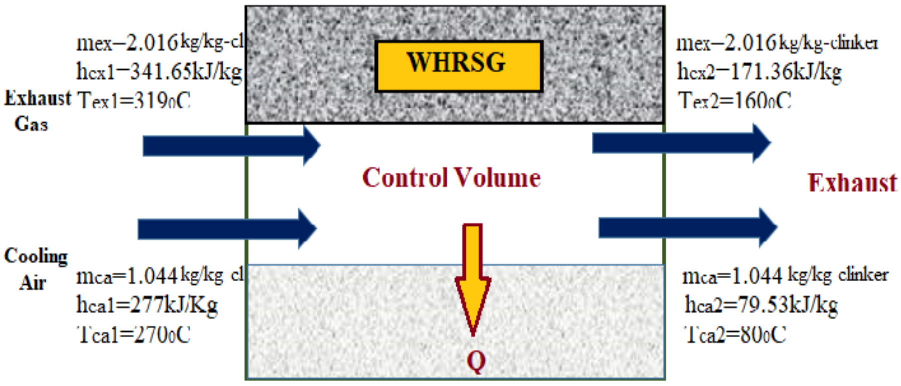

Figure 6. The process diagram of the waste heat recovery steam generator (WHRSG).

Consider a turbine and condenser pressure is 8 bars and 10 kPa respectively, so that the net power obtained from the turbine, is almost 5000 kW. By considering the useful power generated is 5000 kW, the expected savings will be based on the load reduction of 5000 kW. Considering 8000 h of usage, the expected savings become;

Energy saved = (Power generated) * (hours of usage) = 5000kW*8000hr/yr. = $4*10^7$kWhr/yr.

The energy cost of the current factory under the analysis is 0.0211USD/kWh [Berhe, 2012] and hence, the expected cost savings is given by:

Cost savings =0.0211USD/kWh * $4*10^7$kWhr/yr. = 844,000USD/yr.

By considering the average labor and maintenance costs is 40,000 USD annually, the saving becomes 800,000 USD/year.

The implementation cost of this additional system could be the purchase price of important equipment and its installation. The power generation unit may require additional cost for maintenance. By considering the whole system as shown in Fig. 5, a budget is estimated between 1,500,000 – 2,000,000USD, including shipping and installation. Hence, by using a rough estimation a simple payback period becomes:

$$\text{Simple payback period} = \frac{\textit{implementation cost}}{\textit{annual cost savings}}$$

$$= \frac{2{,}000{,}000}{800{,}000} = 2.5\text{yr} = 30 \text{ months}$$

The energy savings by using a WHRSG system is also used to increase the performance of the overall system. Generally, it should be noted that these analysis shows a rough estimation and it depends on plant conditions and other economic factors.

Use of Waste Heat to Pre-Heat the Raw Material

Preheating raw material and coal before the clinkering process is the most effective method of recovering waste heat in cement plants. In this method gas streams are directed into the raw material just before the grinding mill. This would result increasing the efficiency of grinding the raw material in addition to increasing of its temperature. However, in most cement plants, the fresh raw material and coal taken from the mill is not directly enter to the kiln, and therefore, the temperature increase of the raw material is not useful because it will be stored in silos for some time just before entering the clinkering process. On the other hand, some plants may have only kiln systems instead of grinding systems. In this case some additional modifications have to be made in the plant [Tahsin, 2004 and 2011].

In this study our cement plant has grinding mill and applying preheating technique could save high amount of energy. The main purpose of pre-heating raw material in the mill is drying the material, because it is moisty in nature. By considering, the moisture content of the raw material i.e. 6% and a mass flow rate of water of 2.315kg/s (0.1 kg/kg-clinker) enter into the mill. Mixing of the two main hot gas streams would result in a single gas flow at about 3000C, as shown in Fig. 7. By applying the conservation of mass and energy principle for the mill (neglect heat losses) which leads as to increase of temperature of the raw material by 860C, but the gas stream cools down to 1700C. It is made evident that the majority of the useful energy have to be used to heat the water from 24 to 1100C, and to vaporize completely it at this temperature [13, 14]. The energy balance for the mill system is given by:

$$Q_{\text{gas flow in}} + Q_{\text{moist raw material}} = Q_{\text{water}} + Q_{\text{gas, out}} + Q_{\text{dry raw material}}$$

$$Q_{\text{gas, out}} = 23.15[(3.06*321.3) + (1.78*20)] - 2.315(461.3 - 100.7 + 2230.2) - 23.15(1.68*94.6)$$

$Q_{\text{gas, out}}$ = 13,908kW $h_{\text{gas, out}} \approx 175$kJ/kg $T_{\text{gas, out}} \approx 170^0$C

Where, hf@24^0C =100.7kJ/kg, hf@110^0C = 461.30kJ/kg, hfg@110^0C =2230.2kJ/kg.

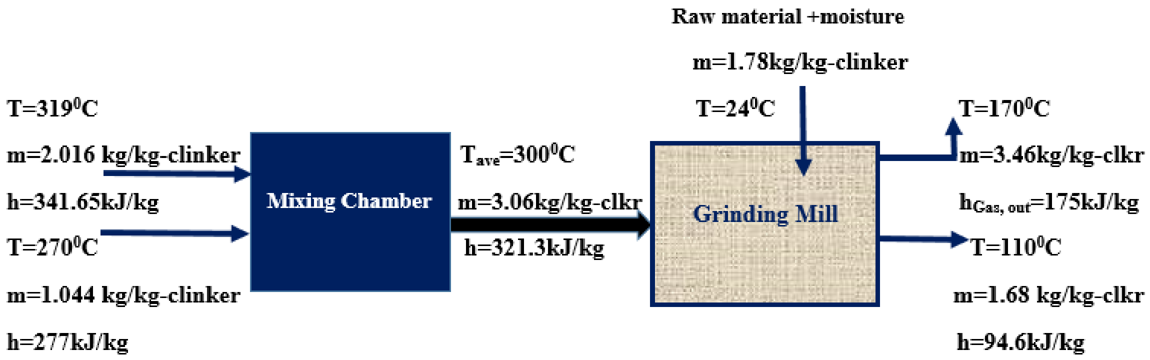

Figure 7. Mass and energy balance for grinding mill.

CONCLUSION

The main aim of this study is to determine the heat lost and discussing the recovering mechanisms. By using the actual plant operational data mass and energy analysis were carried out. From the results which we are obtained, the system efficiency is 51% and the major heat loss sources are preheater exhaust (19.53%) and cooler stack (16.22%) of the total input energy. In order to recover these heat lost WHRSG system is selected and designed. By applying this recovering mechanism 5 MW of energy could be recovered, which means 6.12% of the total input energy is recovered. The anticipated payback period for the systems is to be less than 2.5 yr. Electricity Production with own power using heat lost from the process will enable as to reduce electrical consumption from national grid supply and also decreases clinker production cost. Hence, in order to minimize energy consumption and manufacturing costs WHRSG system have to be implemented in the design of new plants. It is recommended that Ethiopian government should have to give great concern for cement industries by supporting this WHRSG implementation through exemption of tax and other incentives.

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NOMENCLATURE

M	Mass
Q	Heat
C	Specific heat capacity
σ	Stefane Boltzman constant = 5.67×10^{-8} $W/m^2 K^4$
ε	Emissivity of the surface (for oxidized surface = 0.78)
T_∞	Ambient temperature
Nu	Nusselt number.
Ra	Rayleighs number
h_{ncon}	Natural convective coefficient
h_{fg}	Enthalpy of moisture per unit mass(kJ/kg)
h_g	Enthalpy of saturated vapor per unit mass(kJ/kg)
k	Thermal conductivity of the material
A	Area of the rotary kiln
E	Radiative heat transfer (heat flux)
h	Heat transfer coefficient
F_{12}	View factor that takes (=1)
η	The overall system efficiency

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