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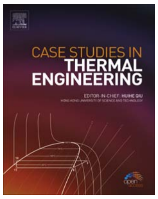

Assessment of waste preheater gas and dust bypass systems: Al-Muthanna cement plant case study

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ABSTRACT

Preheaters are used industrial dry kiln cement production plants to heat the raw mix and drive off carbon dioxide and water before it is fed into the kiln. An analytical model of a generalized four-stage suspension cyclone preheater system is presented. This model was used to study the influence of waste preheater gas and dust bypass systems on preheater performance and efficiency. As the bypass size (percentage) was varied, the heat content of the bypass gas was calculated for different constant calcination degrees. The results showed that the heat content, respectively for each cyclone (I, II, III, and IV), is: 542.0, 801.9, 1034.3 and 1192.7 kJ for a calcination degree of 90% and bypass percentage of 40% bypass. Changing the calcination degree to 50% and bypass percentage to 40% resulted in gas heats of: 541.4, 801.0, 1033.2 and 1191.5 kJ, respectively for each cyclone. These results show that the calcination degree is inversely proportional to the heat content of waste preheater bypass gases. While increasing of bypass opening at constant the amount of dust kiln gas will cause decreasing of waste heat content of kiln gases.

1. Introduction

Modern cement production pyro-processing involves calcination and sintering processes that generally take place in a rotary kiln. The objective is to create clinker (aggregate alite nodules) from raw mix (ground limestone mixed with clay or shale). Modern cement industries use both wet and dry rotary kilns. In a wet rotary kiln the raw mix contains approximately 36% moisture. Wet kilns improve control of the size distribution of the raw mix in slurry form, but they require more energy than dry kilns in order to evaporate the moisture content in the raw mix. In the past, wet kilns were generally preferred over dry kilns. This changed in the 1980s when improved grinding methods were developed that reduced the need for particle fineness control in the kiln. Dry kilns now dominate the modern cement industry, which is the subject of this paper.

In dry kilns, raw mix with low moisture content (e.g. 0.5%) is used, reducing the need for evaporation and reducing the length of the kiln. The raw mix is fed into a combined preheater and precalciner apparatus, which heats and partially (nearly completely) calcinates the raw mix before it reaches a rotary kiln (Fig. 1) [1,2]. The calcination process involves the thermal decomposition of calcite and other carbonate materials to form metallic oxides (primarily CaO) and carbon dioxide gas. The precalciner reduces the fuel consumption in the kiln, because the kiln no longer has to perform the calcination function. Use of suspension preheaters, consisting of a series of staged cyclones, alsoimproves the energy efficiency. The preheaters raisethe temperature of the raw mix, using heat produced by combusting fuel or from hot gases fed from the kiln exhaust. This pre-heating drives off carbon dioxide (up to 90%) and water in the raw mix before it enters the kiln. Most suspension

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Nomenclature

a_{1-4}	constants
B_f	percentage of fuel burning in rotary kiln
B_y	bypass opening (%)
C_p	specific heat at constant pressure ($kJ/kg_{clinker} \times K$)
CD	kiln feed calcinations degree (%)
E_s	cyclone separation efficiency (%)
G_k	ignition loss of kiln dust (%)
$In(i)$	total material inlet to cyclone ($kg/kg_{clinker}$)
KD	quantity of kiln dust reaching to preheater system ($kg/kg_{clinker}$)
$M(i)$	material from cyclone (i) ($kg/kg_{clinker}$)
MK	heat content of bypass gases($kJ/kg_{clinker}$)
Q_{By}	heat content of bypass gases($kJ/kg_{clinker}$)
$Q_g(i)$	heat content of gases from cyclone (i) ($kJ/kg_{clinker}$)
$Q_s(i)$	heat content of dust from cyclone (i) ($kJ/kg_{clinker}$)
Q_{tc}	total specific heat consumption ($kJ/kg_{clinker}$)
RR	quantity of $CaCO_3$ in 1 kg of raw mix(%)
Rc_{1-3}	reaction factors of free moisture evaporation chemically bound moisture evaporation, carbonation reaction and calcination reaction respectively.
$S(i)$	dust from cyclone (i) ($kJ/kg_{clinker}$)
SL	raw mix preheater leakage
S_k	kiln dust
T_c	cyclone temperature (K)
T_k	temperature of exit gases from kiln (K)

Subscripts

kd	kiln dust

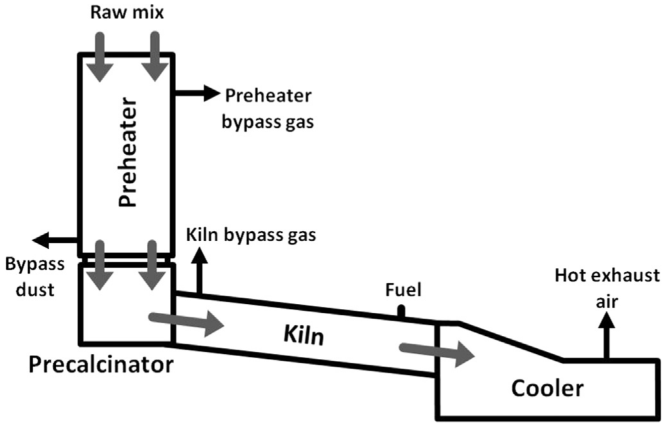


Fig. 1. Pyroprocessing processes in a dry kiln cement production plant.

preheaters are equipped with four cyclones. Cyclones are conical vessels that tangentially intake the raw mix producing a vortex. Volatile solid compounds (e.g. alkalis, sulfates, and chlorides etc.), normally referred to as dust, are separated from the stream by centrifugal forces and exhausted through a bypass system (ERA, http://www.eratech.com/papers/pdf/volatility.pdf). This both cleans and efficiently heats the raw mix. Hot preheater waste gases are also removed through a bypass. Removal of this gas allows higher specific energy consumption (about 6-12 MJ/tonne clinker per percent of removed gas at the inlet of kiln) [4]. The sensible heat of this waste gas is a source of energy loss, although the cyclones minimize this loss by efficiently cooling the gas [5].

The mix is then fed into a rotary kiln where it is sintered to produce clinker. Sintering (or burning) isa thermo-chemical process induced by exposure to hot combustion gases (1800–2000 °C). The kiln waste gases produced by this process are removed through a bypass. Lastly, the clinker is rapidly cooled (100–200 °C). Pyro-processing accounts for approximately 90% of the thermal energy required in cement manufacturing [6].

Several papers have focused on improving the energy efficiency of cement production by using the waste heat of gases in power co-generation systems or improving the cyclone thermal performance. Steinbliss [7] introduced a method of converting the waste gas heat discharged from precalciners into useful power, by ducting the gas into a boiler which runs a steam turbine. Similarly, Khurana et al. [8] presented a thermodynamic analysis of power co-generation using waste heat streams in a cement production plant in India. Camdali et al. [9] performed an exergy and energy analysis of a rotary burner with pre-calcinations. Kolip [10] presented an exergy and energy analysis of a serial flow, four-stage cyclone pre-calciner. Kolip and Savas [11] performed a similar analysis for a parallel flow, four-stage cyclone pre-calciner type. Madlool et al. [12] reviewed the energy use and savings in the global cement industry. In another paper, Madlool et al. [13] reviewed the exergy analysis, balance, and efficiencies ofthe global cement industry. Watkinson and Brimacombe [14] conducted experiments to study the relation between calcination and heat transfer (as a factor of temperature and particle size). However, more research is needed on these topics to optimize the energy efficiency of cement production plants. This paper presents a thermodynamic analysis of preheater bypass gas and dust for varying bypass percentages (B_y) and calcination degrees (CD).

2. Analytical methodology

A generalized four-stage suspension cyclone preheater system is analytically modeled and analyzed. Factors that affect the heat transfer rate in the preheater include: bypass size, calcination degree (CD), temperature, raw mix moisture content, and the amount of excess air (which limits gas production in the system). The mass balance of each phase (solid raw mix and gases) is affected by the reactions taking place in each cyclone. The mass and heat balances can be described mathematically by the following system of equations [15,16,17]:

To balance the materials with dust across each cyclone;

$$M(i) = E_s(i) \times In(i) \tag{1}$$

$$S(i) = In(i) - M(i) \tag{2}$$

Mass inlet to preheater=mass outlet from preheater to (rotary kiln+lost to atmosphere)

$$MK + KD = \left[M(4)/\left(Rc_1 \times Rc_2 \times Rc_3\right)\right] + SL \tag{3}$$

Where

$$KD = (1 - B_y) \times sk \times (1 - G_k) \tag{4}$$

$$M(iv) = (Rc_1 \times Rc_2 \times Rc_3) \times \left[MK + KD - SL\right] \tag{5}$$

$$SL = S(I)\left[\frac{1}{Rc_1}\left(1 - \frac{S(II)}{Inl(I)}\right) + \frac{1}{Rc_2}\left(1 - \frac{S(II)}{Inl(I)}\right)\right] \tag{6}$$

$$M(III) = MK \times [1 + (B_y \times sk \times (1 - G_k)) + S(II)] \tag{7}$$

By using the general energy equation to calculate the heat balance across each cyclone and (bypass percentage):

$$Q = \dot{m} \times C_p \times T_c \tag{8}$$

$$\begin{aligned} Q_g(i) = {} & [a_1 \times Q_{tc} \times (1 - B_y) + a_3\{1 - (1 - CD) \times B_y)\}] \times T_c(i) \\ & + [a_2 \times Q_{tc}(1 - B_y) + a_4\{1 - (1 - CD) \times B_y\}] \times T_c^{\,2}(i) \end{aligned} \tag{9}$$

$$Q_s(i) = S(i) \times (0.206 + 8 \times 10^{-5} \times T_c(i)) \times T_c(i) \tag{10}$$

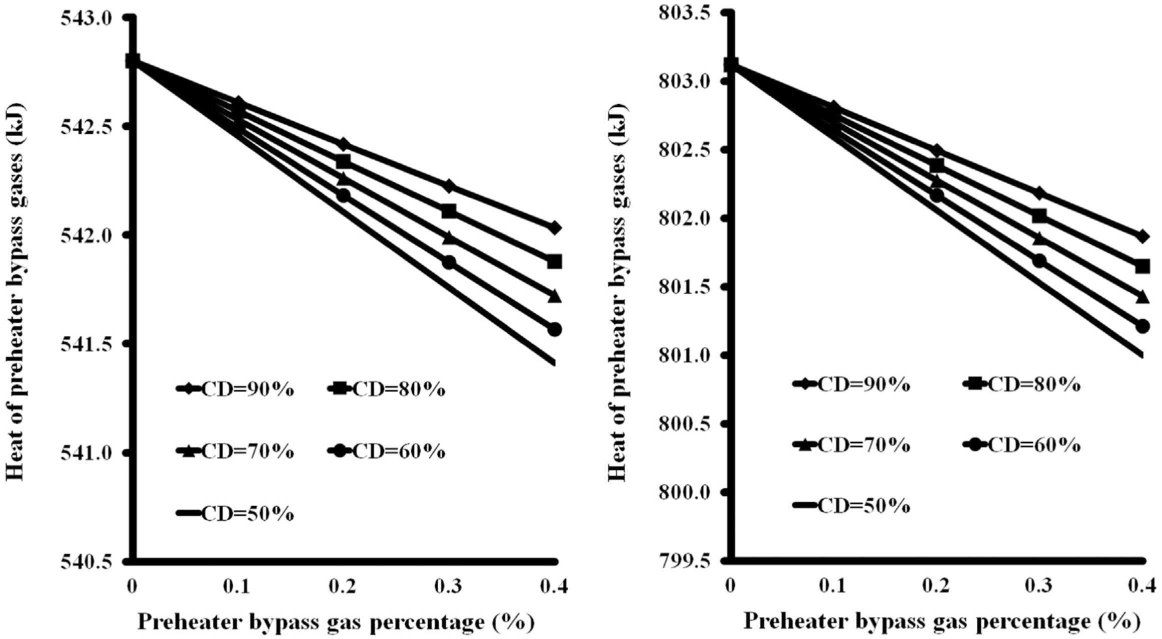
The value of heat lost by gasses exit kiln by (bypass percentage);

$$\begin{aligned} Q_{By} = B_y \ & [(B_f \times a_1 \times Q_{tc} + a_3(1 - CD) + C_{p,kd} \times sk) \times T_k \\ & + (B_f \times a_2 \times Q_{tc} + a_4(1 - CD)) \times T_k^2] \end{aligned} \tag{11}$$

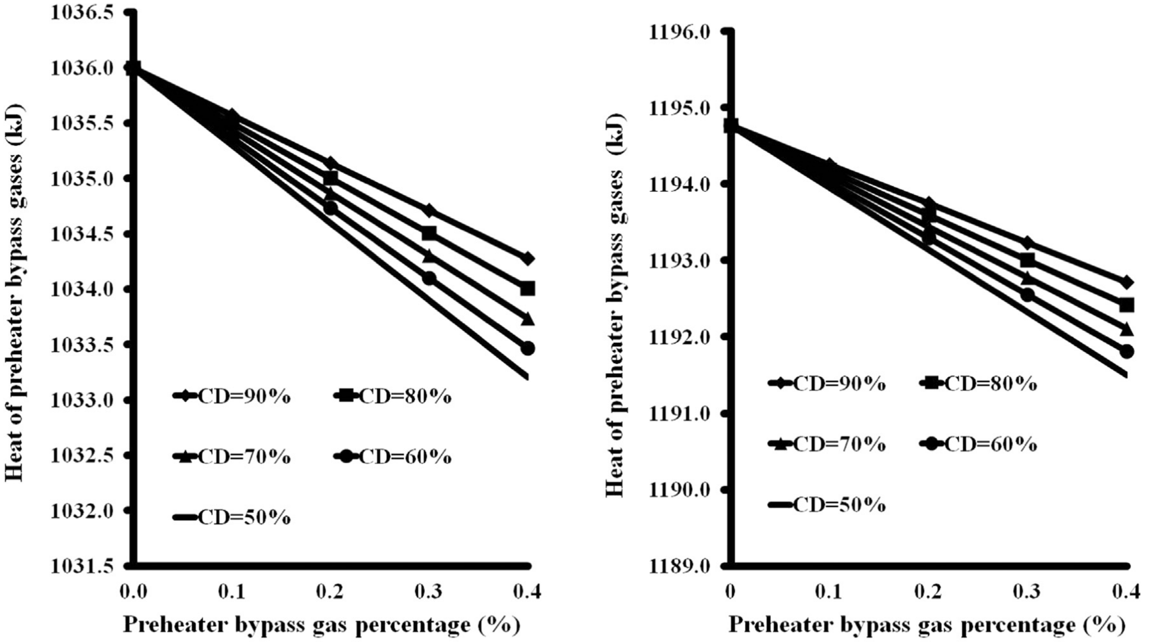
The parameters which were used for preheater system are tabulated in Table 1.

Table 1
Operating conditions for the preheater system.

Symbol	Value	Unit
a_1	4.532×10^{-6}	1/K
a_2	0.721×10^{-6}	$1/K^2$
a_3	0.4903	$(kJ/kg_{clinker}\ K)$
a_4	1.7×10^{-4}	$(kJ/kg_{clinker}\ K^2)$
$C_{p,kd}$	$0.1945+5.55{*}10^{-6} \times T_k$	
$E_s(I)$	95	%
$E_s(II)$	80	%
$E_s(III)$	65	%
$E_s(IV)$	55	%
T_k	1423	K
S_k	0.19	$kg/kg_{clinker}$
G_k	5.95	%
MK	1.92	$kg/kg_{clinker}$
T_s	313	K
RR	85	%
Q_{tc}	3636.6	$kJ/kg_{clinker}$
C_m	0.7	%
B_f	40	%



(a) Cyclone I (b) Cyclone II

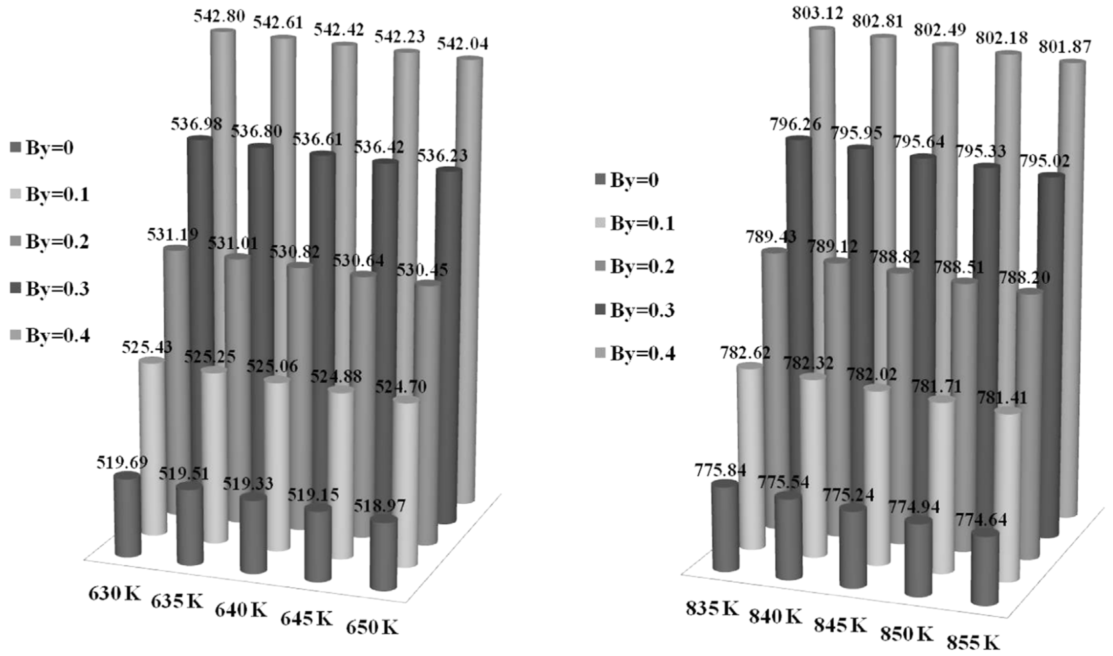


(c) Cyclone 3 (d) Cyclone IV

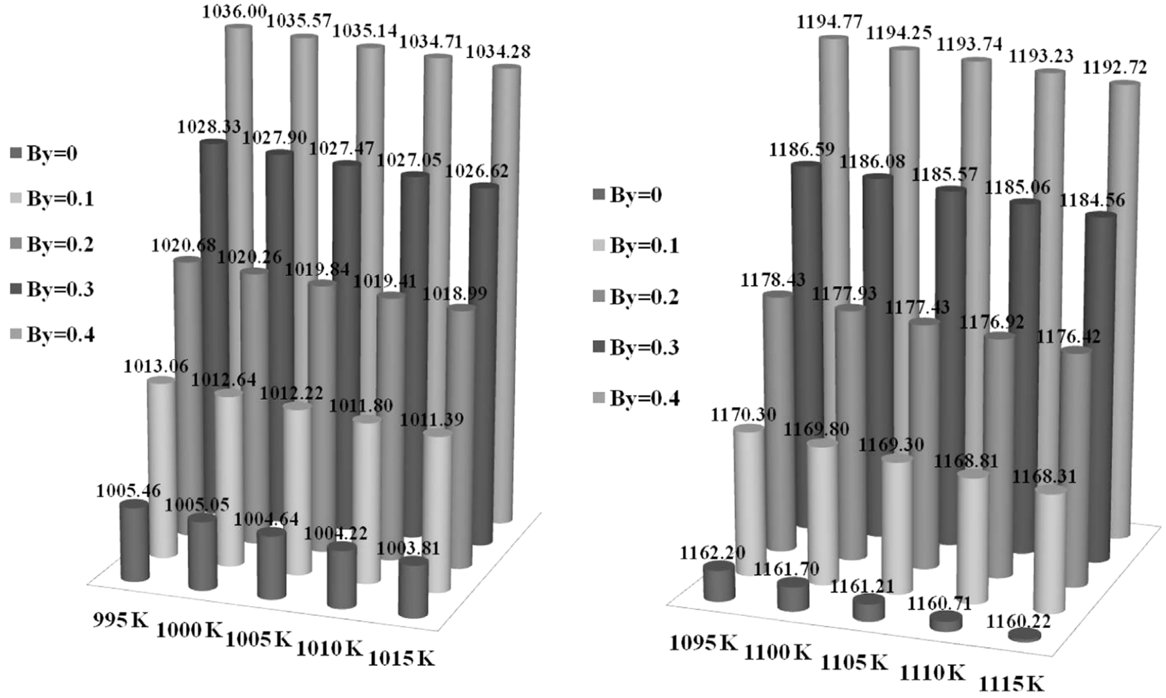
Fig. 2. Heat of preheater bypass gases (Q_g) versus bypass percentage (B_y).

3. Results and analysis

The focus of this analysis is to study the amount of sensible heat lost in the waste gases extracted in the preheater bypass duct, since this constitutes a large source of energy loss. Fig. 2a–d shows that the heat content of these gases decrease as the bypass percentage increases(i.e. caused by widening the bypass passage), when the calcinations degree (CD) is held constant for Cyclones I,II,III, and IV respectively. At constant of bypass opening percentage it is found that the heat content of kiln gases is directly proportional with calcination degree. Fig. 2 also shows that the heat of waste gas decreases as the calcination degree is reduced.



(e) Cyclone I (f) Cyclone II



(g) Cyclone 3 (h) Cyclone IV

Fig. 3. Cyclone temperature (T_c) versus bypass percentage (B_y).

Relatively, the effects of bypass opening percentage and calcination degree cause low losses of heat content of kiln gases.

Fig. 3a–d shows the temperature effect of Cyclones I, II, III, and IV, respectively on the preheater bypass gases. The figure shows that the heat content of gases decreases with increasing cyclone temperature. The bypass effect is inversely proportional to the heat content of bypass gases.

Figs. 4 and 5 show the heat versus temperature of the preheater bypass gases and the bypass dust, respectively. Fig. 5

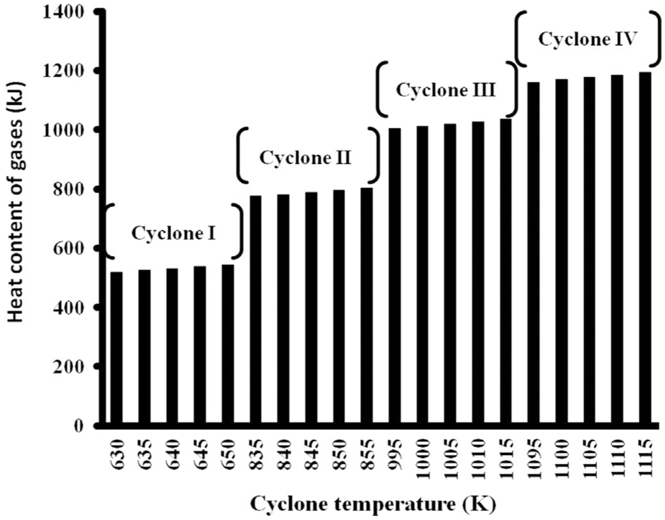


Fig. 4. Effect of cyclone temperature (T_c) on the preheater bypass gas heat (Q_{By}).

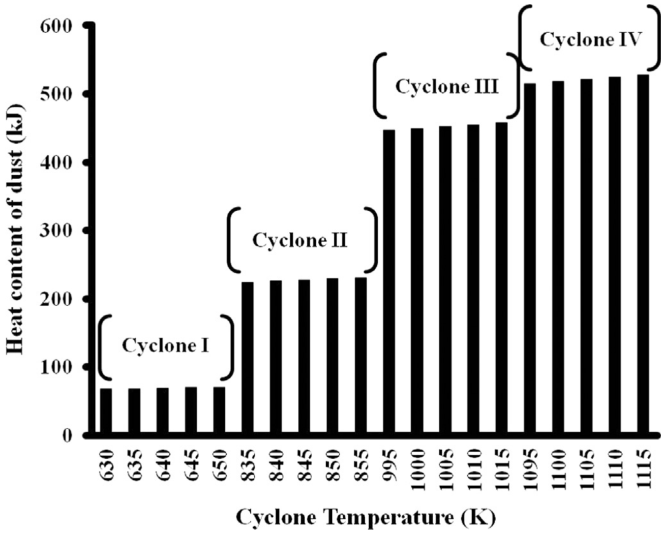


Fig. 5. Effect of cyclone temperature (T_c) on the preheater bypass dust heat (Q_s).

shows incremental increases in gas heat of approximately 1%for every 5 K temperature increase through the series of cyclones. Fig. 6 shows that the dust heat content increases by 0.9% for every 5 K increase in temperature.

Fig. 6 shows the heat content of the preheater bypass gas versus the bypass percentage, while holding calcination degree constant. The heat content of the bypass gases increases as the calcinations degree decreases or bypass percentage increases. If the bypass percentage is held constant, the heat content decreases as the calcination degree increases. Increasing the bypass percentage will decrease the total energy required for calcination.

4. Conclusions

The results can be summarized as follows:

1. Increasing the bypass percentage causes a significant increase in the calcinations degree. The analysis showed that 89–97% of calcination can take place in the pre-heating system for dry kiln cement production.
2. Increasing of calcinations degree (while keeping a constant of bypass percentage) increases the heat content of gases.
3. Decreasing of bypass percentage (while keeping a constant calcination degree) will increase the gas heat content.
4. Incremental increases of gas and dust heat occurred through the series of cyclones. This was approximately 1% for the gas and 0.9% for the dust heat content for every 5 K of temperature increase.

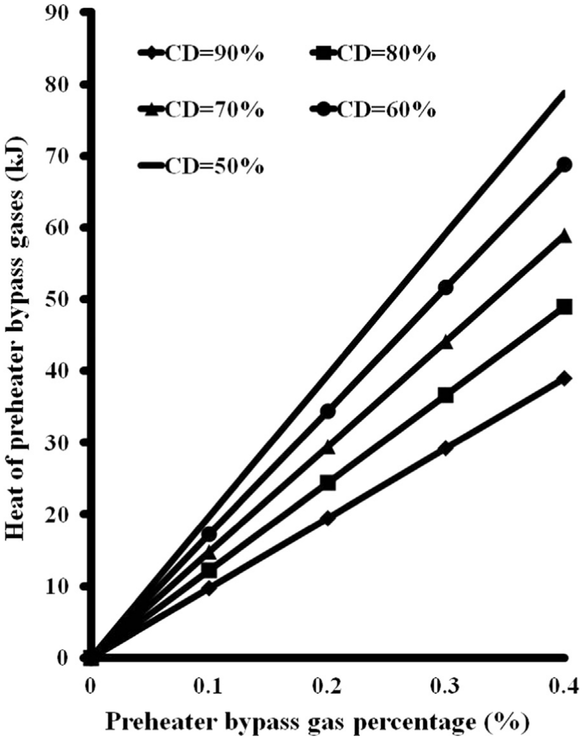


Fig. 6. Preheater bypass gas heat versus bypass percentage.

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