ISSN: 0975-766X
CODEN: IJPTFI
Available Online through ***Research Article***
www.ijptonline.com

SPECIAL FEATURES OF FUEL COMBUSTION IN DRY AND WET PROCESS CEMENT KILNS

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Received on: 15.10.2016 *Accepted on: 12.11.2016*

Abstract.

The cement production involves burning of Portland cement clinker in rotary kilns of various production method; they impose special requirements for the efficient fuel combustion, design of burning devices and auxiliary equipment. An important condition for the energy efficiency of such thermal units is the use of the basic principles of thermal engineering and thermodynamics in the rational approach to flaming of fuel in a "closed" space, heat and mass transfer process management, use of alternative types of fuel. The calculated data and industrial tests found the optimum amount of gas fuel and wood chips with moisture content of 30% that are supplied to a burner and used as an alternative fuel. The number of wood chips burned in a kiln amounts to 4 t/h.

Key words: Temperature, flame, clinkering zone, burner, jet momentum, clinker cooler, exergy, alternative fuel.

Introduction

The process conditions for the cement clinker production in the rotary kilns' clinkering zone make certain demands to the conditions of fuel combustion [1-5]. It is known that the clinkering zone is combined with the fuel combustion zone. The length of clinkering zone in long powerful kilns usually coincides with the length of the fuel flame. The fuel combustion temperature should ensure the completeness of physical and chemical processes of formation of clinker minerals determined by the properties of the kiln feedstock mixture. Compliance of the fuel combustion parameters with the clinkerization parameters of feedstock mixture is the most important condition for the clinker burning process in the rotary kilns.

Main part

The fuel flame is burning in the zone under conditions of relatively low heat consumption, and the temperature of kiln lining and charge is 150-400°C lower than the flame temperature. The average flame temperature in the fuel combustion zone is, depending on the production method, about 1650-1850°C.

The calculations of heat balances in the fuel combustion zone imply that the wet production process with a specific heat consumption of 5.4-6.5 MJ/kg of clinker consumes 3.5-4.5% for heating the material to the clinkering temperature and about 6% for kiln body's heat losses in the clinkering zone. The heat dissipation of flame does not exceed 10% of the total flame heat in this section of kiln.

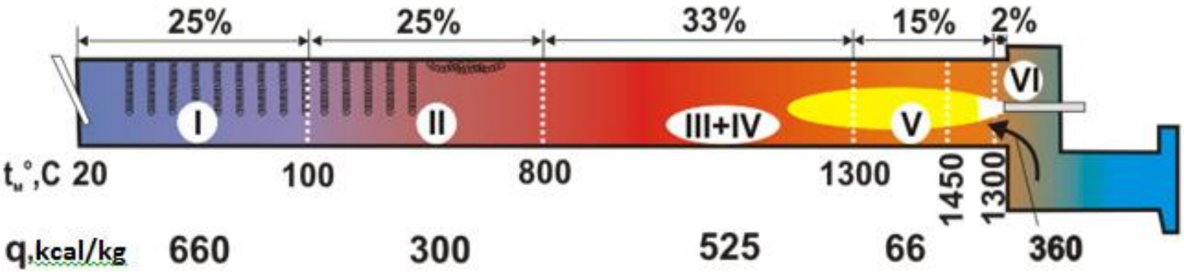

Figure 1. Process zones in wet process kiln and heat consumption in the zones.

Low heat dissipation to the material and high temperature provide a stabile combustion process.

The clinker can be burnt in different combustion zones: "long or short", "distant or near". All conditions have their positive and negative aspects, and they are determined by the design features of kilns and working methods. Working on the "short" zone enhances the clinker activity, but it increases the thermal stress due to the concentration of high temperatures on a small section of kiln length, which causes destruction of the coating and lining and contributes to the material rings. Working on the "long" zone reduces heat influence on the lining, but it limits the kiln productivity. The flame can not be practically elongated in the dry process kilns, since it is limited with temperature parameters of the material in the external heat transfer devices, heat resistance of their constructions and kiln length.

The special features of the fuel combustion in rotary kilns should include the requirements to the combustion zone position by temperature of the clinker emerging from the kiln; such temperature should not exceed 1200-1250°C, and temperature of the body - 250-300°C.

Without going into the special features of preparation for burning different fuels and the impact of kiln working parameters on qualitative data of the products, let us consider the efficiency of fuel combustion techniques. It should be recognized that the decisive factor in the efficiency of fuel combustion is the temperature, which determines the speed of chemical processes during the synthesis of Portland cement clinker; such processes are subordinated to

Arrhenius exponential relationship. Because the flame temperature in dry process kilns is 100-200°C higher than in the wet process kilns, the performance of such kilns could be improved at a relatively small size of units.

Significant attention is paid to the intensification of heat transfer in a kiln between the material and gas flow and to the fuel economy. Many years of experience of the Department for Technology of Cement in the BSTU named after V.G. Shukhov confirmed in practice the importance of heat conservation in the hot part of the kiln [1].

Considering the exergy (efficiency) of the heat flow of the combustion products ($E_{c.m.}$) obtained from the combustion of 1 kg of fuel, the following can be written:

$$E_{c.m.} = H_T \cdot \left(1 - \frac{T_0}{T_T}\right),$$

where: $H_T = Q_i \cdot \eta_f + Q_{air} + Q_{fuel}$ is theoretical enthalpy, kJ/kg;

$T_T = \left(\frac{H_T}{\sum V_i \cdot C_{c.m.i}}\right) + 273$ is theoretical combustion temperature, K;

T_0 is ambient temperature or temperature of the combustion products in the selected section of a rotary kiln; η_f is kiln efficiency; Q_{air} and Q_{fuel} are heats introduced into a kiln with air and fuel, respectively, kJ/kg.

The above formulas show that with increased air and fuel heating and reduced volume of the combustion products at lower air excess coefficient [alpha], the heat flow efficiency is growing since thereby H_T and T_T increase. The actions, which increase $E_{c.m,}$ will contribute (under otherwise equal conditions) to reduced exergetic loss during the heat transfer from the combustion products to a heated body. Thus, considerable attention should be paid not only to the reduction of heat losses during heat recovery of clinker, but the highest possible temperature should be also sought to obtain in the fuel combustion zone; it can be achieved by improving the burners and effective parameters of a kiln unit.

Reducing the heat loss with clinker and increasing the enthalpy of the secondary air are determined by the clinker cooler's operation. The most important indicator of the cooler's efficiency is its heat efficiency. Only when the clinker cooler's efficiency reaches at least 0.8, economical operation of the wet process kilns is ensured. Although the heat losses associated with cooling of clinker amount to about 5% of the total heat consumption, savings under this article of the heat balance are paramount. The essence of such high efficiency of heat conservation in cooling the clinker is that a part of the fuel heat is replaced with the heat of hot secondary air. This reduces the volume and speed of the kiln gases and significantly increases the heat transfer in a kiln. In practice [7], it reduces the temperature of the exhaust gases, improves the conditions for formation of coating in clinkering zone, decreases the kiln body's temperature and, therefore, reduces the heat losses to the environment.

Considering the physical conditions of heat transfer in the clinkering zone, it should be noted that the flame radiation transfers up to 80-90% of the heat. The famous Stefan-Boltzmann law applies to the heat transfer by radiation. With the Bloch's additions [8], the radiant heat transfer for a rotary kiln is determined by the formula:

$$Q_r = 5{,}67 \cdot [\text{epsilon}]_m \left[[\text{epsilon}]_{flame} \left(\frac{T_{flame}}{100} \right)^4 - a_g \left(\frac{T_m}{100} \right)^4 \right],$$

where Q_r is heat flow density of radiant energy; $[\text{epsilon}]_m$ is blackness degree of the material; $[\text{epsilon}]_{flame}$ is blackness degree of the flame; a_g is gas absorption capacity at a temperature equal to the temperature of the material; T_{flame} and T_m is temperature of the flame and material.

With an increase in the flame temperature, for example, by 100°C, in the temperature range of 1550-1650°C, the radiant heat transfer grows by 23%. However, an increase in the kiln temperature is limited by the stability of the refractory lining and clinker synthesis conditions. To intensify the heat transfer process is possible at a lower temperature of flame, but it is necessary here to create certain conditions, under which $[\text{epsilon}]_g$ - its blackness degree will increase ($[\text{epsilon}]_g$ can vary from 0.25 to 0.7). Creating a rational fuel combustion conditions in a kiln is of great importance, and it is largely determined by the design of burners.

All combustion processes have the following stages: *Mixing→Inflammation→Chemical reaction→Dissipation of products*.

The combustion rate depends on the speed of the above stages. In most industrial combustion systems, mixing is the slowest stage, while other stages are fast. Therefore, the combustion rate and completeness are controlled by the fuel-air mixing rate and completeness, i.e. the oxidant-to-fuel input rate and their mixing intensity, and they are determined by the Peclet criterion:

$$P_e = P_r \cdot R_e = 0{,}7 \cdot R_e$$

The Reynolds criterion:

$$R_e = (w \cdot d)/[\text{nu}]$$

where: d is a determining diameter (kiln diameter); w is a gas flow rate; [nu] is a kinematic gas viscosity.

With an increase in the burner gas rate, and the mixing and combustion intensity grows, with an increase in the secondary air temperature, the mixing and combustion rate slows down, since the air viscosity significantly increases. The flashpoint determines a flame configuration. Early inflammation in diffusion burners deteriorates the oxidant inlet and slightly lengthens the flame, which should have the optimal configuration.

During combustion of the medium pressure gas in a rotary kiln, single-channel and less frequently dual-channel gas burners are used. The intensive mixing of gas and air is achieved in these burners because of the high degree of gas flow turbulence at high rates of gas outflow from a nozzle. They have a relatively small diameter and can operate without swirlers. The installation of swirlers ensures the improved contact of the gas mixture with the kiln charge and the intensive combustion process due to the efficient mixing of gas with air. The intense combustion and good contact with the kiln charge during installation of swirlers are attributed to the fact that it forms the maximum possible number of sources of heat due to the contact of the flame with the heated surfaces of both the kiln lining and charge. As the practice [9] of studying the natural gas combustion in rotary kilns shows at average gas pressures from 0.4 bar and at a flow rate of 300-400 m/sec in small diameter single-channel diffusion burners, gas burns intensively without chemical incomplete combustion at values of air excess coefficient [alpha]> 1.05.

However, the application of such burners has a substantial disadvantage, which is in a high concentration of fuel in the flame axis. This determines forming the peak temperature load on the body in a kiln depending on the burner mode (gas pressure, position of swirler, heat flow efficiency in a kiln, etc.) in the "near, middle or distant" burning zone and forces to use the techniques lowering the fuel combustion intensity (e.g. by increasing the burner's slope to the material); this ultimately decreases the heat transfer effectiveness.

To intensify the combustion of the gas mixture, a developed and stable ignition of the mixture by crushing the flow into small jets and creating stable centers of ignition should be arranged. Stable ignition means a burner's ability to ensure ignition near the burner's slot at a possibly higher flow rate of the combustible mixture. The developed ignition and combustion surface reduce the inert volume of the flame and increase the thermal stress of its volume. Transition to the slot burners, in which developed ignition is conducted through an increased inflammation perimeter, can be considered appropriate. In this case, the flame takes the form of a hollow diverging cone, in which ignition is carried out both on the burner's periphery and along the inner surface of the flame through the intensive recirculation. The combustion products are captured from the flame and ignite the incoming fuel. The internal recirculation zone can be achieved by the following methods:

- presence of bluff body in the burner's nozzle;
- swirling of fuel;
- swirling of primary air;
- swirling of fuel and primary air

Achieving a good stability of the natural gas flame is really difficult, because it has high inflammation temperature, narrow inflammation limits and low flame velocity. Stabilization of the fuel oil flame requires appropriate spraying plus consideration of local recirculation.Stabilization of the pulverized fuel (e.g. coal/coke) flame affects fineness of grinding, properties of ash, content of volatile components and rate of coal-air jet.

Swirling of the primary air is a very effective solution to ensure the stabile flame, but the fact should be taken into account that it reduces a share of the secondary air and thus the cooler's heat recovery efficiency. In the dry process kilns, the use of primary air is explained by the necessity of intensification of the fuel combustion, but in the wet process kilns this method raises serious objections. It should also be borne in mind that gas combustion even with high fuel jet momentum (8-9 N/MW) leads to a drastic decay of jet on the circular-clearance burners of larger diameter. The result is that the flame with a very close point of ignition is formed with relatively small involvement of secondary air in the jet. The flame turns "sluggish," and when slightly preheated material enters the clinkering zone the flame can shift in the preparation zones. The geometric parameters of a gas jet should be also considered and, if there are multi-jet nozzles, the necessary impetus should be strived to be given to each of them.

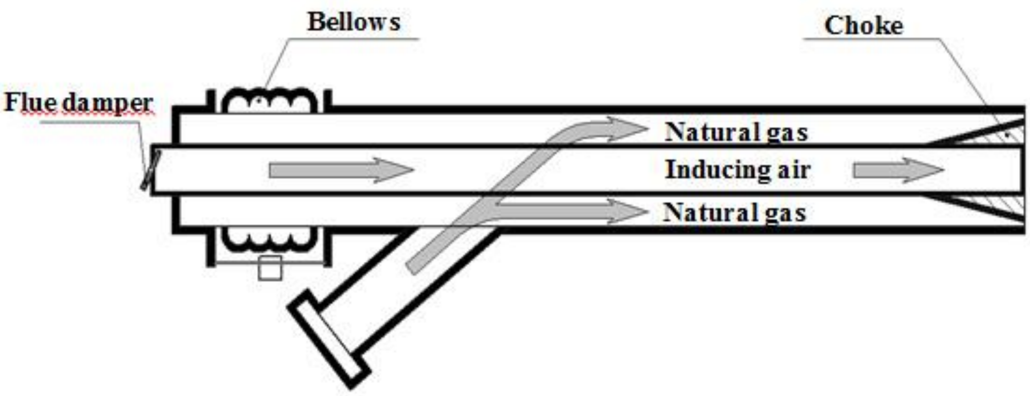

Figure 2. Schematic diagram of burner of GID type (two-circuit injection-diffusion gas burner)

In practice, the gas burners of GID type [10] (injection-diffusion) underwent the industrial approbation at Mordovcement, JSC and Shurovskiy Cement, JSC, Karadag Cement, Sebryakov Cement, JSC; such burners have been designed at BSTU named after V.G. Shukhov together with Ayan, LLC PF, in Tula and provide efficient heat transfer in flame space with high thermal stress of flame volume. The distinctive feature of modification of these burners (Figure 2) is a central channel, through which the primary air is injected by the vacuum created by the gas flow behind a bluff body, which role is performed by a choke configured as an inverted cone. The burner has a wide control range and is high ignition resistance. A free central channel allows burning other types of fuels in a kiln. Currently, the work is underway to optimize the choke design for joint combustion of gas and various types of solid and liquid fuel in a certain combination thereof; it is a very difficult task in view of the different ignition temperatures, caloric content and combustion rate of the combined fuel components.

Mordov Cement, JSC tested the burner of GID type for the possibility of joint combustion of gas and wood chips, and the burner showed good results. The combustion of alternative fuel involves determining the maximum possible amount thereof instead of the traditional energy source - gas.

To evaluate the effectiveness of alternative fuel, which is presented by a wooden sleeper processed to wood chips, let us calculate the heat capacity and maximum flame temperature when such fuel is used with different moisture content (Table 1).

According to the All-Russian Thermal Engineering Institute, the wood is composed of C^{daf} = 51%, H^{daf} = 6.1%, O^{daf} = 42.3%, N^{daf} = 0.6%, A^{d} ~ 1%, Q^{daf} = 4,530 kcal/kg, t = 2,010°C.

The calculations show that the combustion temperature is sharply reduced with increased moisture content of the used wood chips. A at the moisture content of 50%, the flame temperature could be compared with the temperature required to produce the clinker – 1450°C. At completely dry wood, the temperature, which the flame can develop, is comparable with the gas flame. But when the moisture content increases the flame temperature drops sharply. And consumption of wood chips should be restricted depending on their moisture content.

Table 1: Calculated composition of wood chips with different moisture content, %.

	Moisture content of wood chips, %			
	20	30	40	50
As-fired fuel wood chips, %				
C^r	40.8	35.7	30.6	25.5
H^r	4.9	4.3	3.7	3.1
O^r	33.8	29.6	25.4	21.1
N^r	0.5	0.4	0.3	0.3
$\sum$	80	70	60	50
Q^{daf}, kJ/kcal	14698/3510	12558/2999	10418/2488	8290/1980
Combustion air, m^3/kg	3.800	3.328	2.855	2.386

Volume of combustion products, m^3/kg				
V_{CO_2}	0.759	0.664	0.569	0.474
V_{H_2O}	0.797	0.854	0.910	0.967
V_{N_2}	3.006	2.632	2.258	1.887
$\sum$	4.562	4.15	3.737	3.328
Heat capacity, °C	1884	1773	1641	1489

The caloric content of wood does not exceed 1,980 kcal/kg at moisture content of 50% and 3,510 kcal/kg at moisture content of 20%. It should also be noted that the wood moisture content reaches 20% under conditions of natural storage for 2 years. The tests used the wood with a moisture content of 32.1 - 35%.

For the normal heat transfer, the flame temperature should be about 1750°C in the combustion chamber of a kiln.

Reduction of the flame temperature by 30°C will reduce the radiant heat transfer by 6; eventually it will require increasing the residence time of the material in the clinkering zone and lowering the kiln productivity. This is a natural process when using low-calorie fuel. Otherwise, the total heat consumption should be increased.

To determine the number of input of the wood chips, given the decreased flame temperature, in the graph (Figure 3) a horizontal line should be drawn, for example from temperature of 1720°C, and at the intersection with the inclined line of certain moisture content, below, the recommended number of alternative fuel in t/h should be determined according to scale of the "number of input of the wood chips". At the moisture content of 30%, the number of wood chips amounts to about 4 t/h.

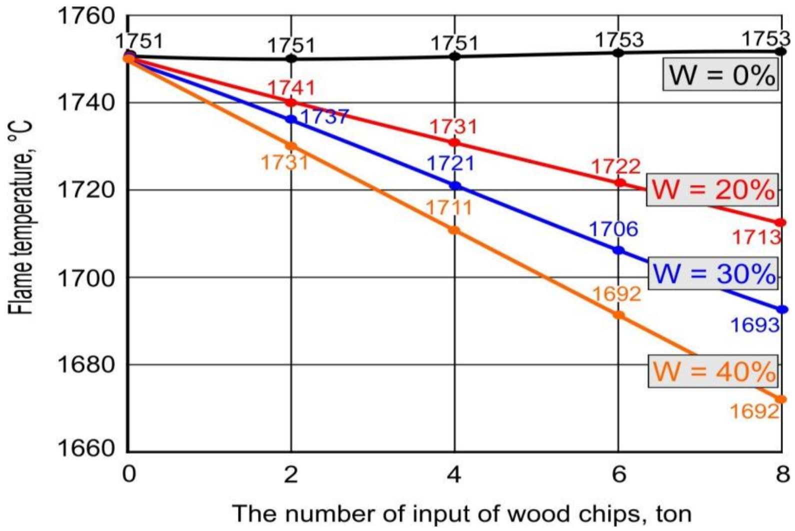

Figure 3. Impact of share of the input of wood chips on the flame temperature given its moisture content

It is also necessary to pay great attention to the clinker cooler's operation because the temperature developed at the fuel combustion depends on the cooler's operation. The calculated relationships between the consumption of wood chips and the cooler's thermal efficiency indicate that at the same moisture content of wood chips their consumption can be doubled when changing the cooler's efficiency from 70% to 90%. The tests carried out on kiln No. 6 have convincingly shown that an increase in the input of wood chips for more than 6 t/h in the kiln leads to higher temperature of the exhaust gases (i.e. the clinkering zone does not provide the adequate heat transfer, and the heat is transferred in the preparation zones); it indicates the need to increase the gas consumption.

Summary

The resulting analytical relationships will allow to specifically determine a rational correlation between the gas and solid fuel consumption to create the necessary heat transfer conditions in the rotary kiln's burning zone. The industrial tests revealed that the number of the wood chips input during combustion of wood chips as alternative fuel amounts to 4 t/h.

Conclusions

1. The flame temperature, which determines the speed of chemical and thermal processes, should be recognized as the main indicator of the fuel combustion efficiency.
2. Heat recovery in the clinker cooler is an essential factor in intensification of the energy-exchange processes ensuring the reduction of natural fuel consumption during the burning process.
3. The flame configuration is defined by the fuel ignition point of the burner's slot; it is explained by the conditions of fuel and oxidant mixing.
4. When using alternative fuel, its heat capacity should be taken into account; it limits the use of low-calorie types of fuel.
5. When selecting burners, the special features of fuel combustion should be considered for dry and wet process cement kilns; such features are due to their size and heat transfer conditions.

Acknowledgement: The studies were conducted with financial support of the Russian Foundation for Basic Research as part of a research project No. НК-14-41-08031 р_офи_м (NK-14-41-08031 r_ofi_m).

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