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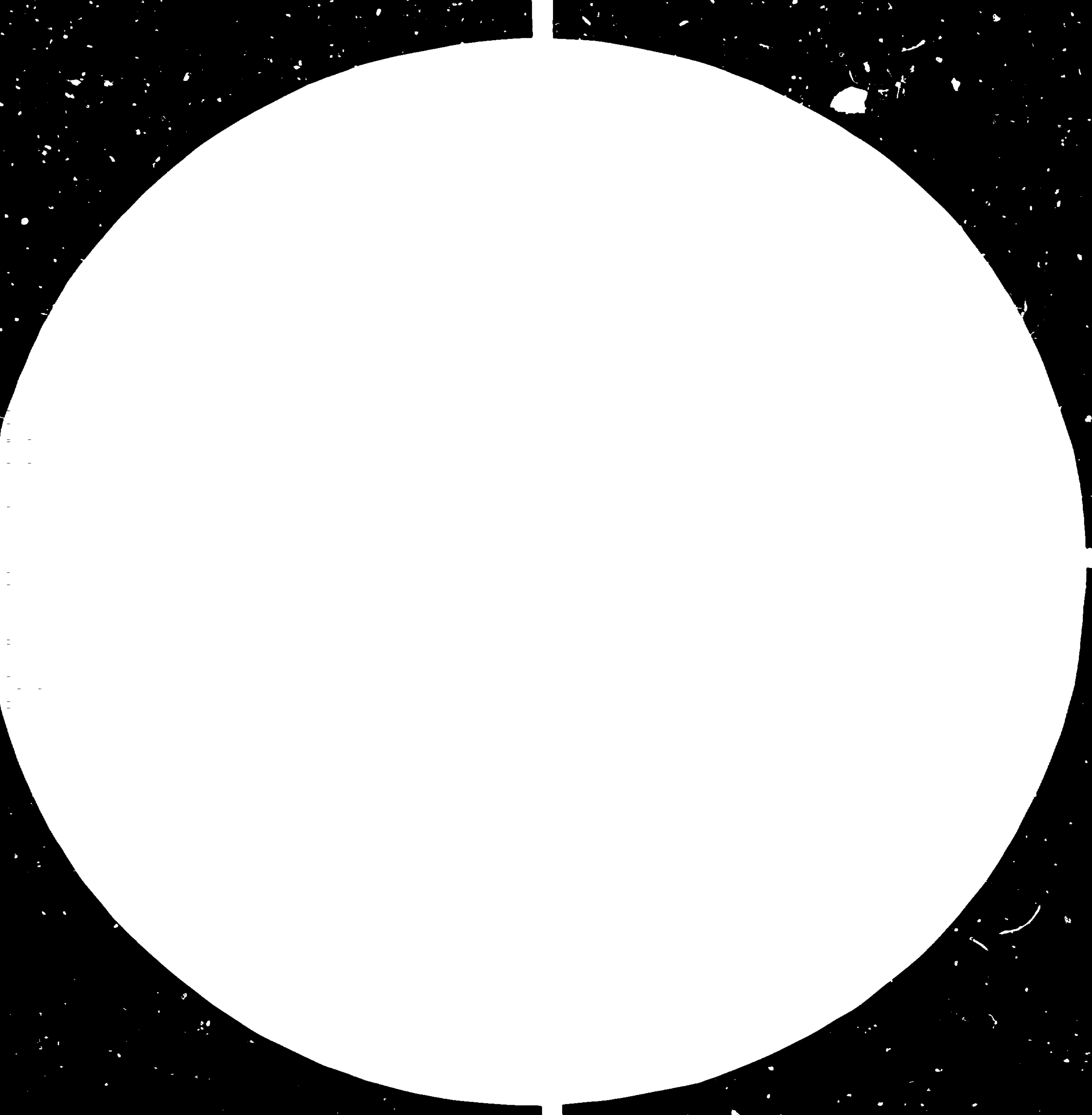

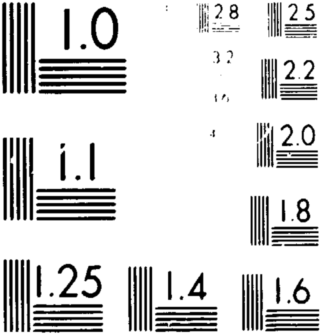
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HEAT ECONOMY OF CEMENT ROTARY KILN *

by

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I. Introduction

Theoretically, 400-430 kcal* of heat are required to produce 1 kg of cement clinker. In practice, however, 750-1800 kcal/kg clinker should be consumed in cement rotary kiln, depending on the manufacturing processes and the types of kilns. This is due to the fact that heat losses are unavoidable in operating a kiln. The ratio of the theoretical heat requirement to the practical heat consumption is defined as the thermal efficiency of kiln. The values of thermal efficiency for various kilns are in the range of 25-55%. For mordern dry preheater kiln, the heat consumption is 750-800 kcal/kg clinker with thermal efficiency 52-55%; for wet long kiln or old type dry process kiln, it is generally 1300-1800 kcal/kg clinker with thermal efficiency 25-35%. The difference between the two is almost twice as much.

Dry process kiln with suspension preheater is generally adopted nowadays for new cement plants. This type of kiln is unexceptionally selected if one wants to improve the heat economy of cement manufacturing. However, there are many wet process kilns and other type dry kilns still in use. in many countries. More than half of the total production of cement are produced by wet kilns in China. Therefore, it is worthwhile to look into the problems for improving the efficiency and operation of various kilns so far as the energy conservation is concerned.

Table 1 lists the main items of heat losses for four different types of rotary kilns. The figures listed denote an average condition of the corresponding kiln.

* 1 kcal = 4.183 KJ

Table 1. Thermal efficiency for different types of rotary kilns, kcal/kg clinker

Item		Wet long kiln		Dry long kiln		Semi-dry Lepol kiln		Dry pre-heater kiln	
		amt.	%	amt.	%	amt.	%	amt.	%
available heat	theo. heat requirement	420	28.98	420	44.07	20	52.11	420	53.57
heat losses due to	evaporat'n.	529	36.51	-	-	109	13.52	-	-
	exit gas	264	18.22	312	32.74	97	12.04	184	23.47
	cooler vent	72	4.97	79	8.29	81	10.05	83	10.59
	clinker	20	1.38	20	2.10	20	2.48	20	2.55
	radiation	144	9.94	122	12.80	79	9.80	77	9.82
total heat cons'n.		1449	100	953	100	806	100	784	100
therm. eff., %		28.98		44.07		52.11		53.57	

It can be seen from Table 1 that the wet process kiln shows lowest efficiency among the four as the heat required for evaporating water amounts to more than one third of the total heat consumption. Since the heat consumption of wet kiln is high, the amount of exit gas produced per kg of clinker is also high, it makes the heat loss due to exit gas 1.4-2.7 times as high as that of Lepol kiln and preheater kiln. The total heat consumption of long dry kiln is lower than wet kiln, but the exit gas loss of the former is much higher. This is due to the exit gas temperature of long dry kiln is higher (400-450°C).

Heat loss due to water evaporation for Lepol kiln is 109 kcal/kg clinker, which is 13.5% of the total consumption; while for preheater kiln it is negligible. However, as the exit temperature of Lepol kiln is lower (ab. 150°C) as compared with preheater kiln (350°C), the exit gas loss is lower. Therefore, the sum of these two items of both kilns is about equal, and the efficiency is also about the same. It must be mentioned, however, that the 184 kcal/kg clinker of heat carried out by exit gas from preheater kiln can further be utilized for drying the raw material. About 50-100 kcal/kg clinker can be recovered depending on the moisture content of raw material. On the other hand, the 97 kcal from Lepol kiln can not be utilized any more as the temperature of this gas is too low. Therefore, additional heat supply for drying is required in a Lepol plant. For long dry kiln, the waste heat in exit gas can also be partly recovered for drying as the temperature is high enough.

The radiation loss of both wet and dry long kilns is 80-100% higher than that of Lepol kiln and preheater kiln. The reason is that not only the kiln proper is longer, but also the specific kiln output is taken lower. The higher the specific output is, the lower the radiation loss per kg of clinker will be.

The heat carried out by cooler vent air is the lowest for wet kiln owing to more secondary air is required in the kiln and vent air from cooler is less. If the vent air could be used for drying raw coal, 15-30 kcal/kg clinker may be recovered depending on heat consumption of kiln and moisture content of coal. This is what happened in grate cooler. For rotary or planetary cooler, there will be no vent loss.

Figures for heat loss due to clinker listed in Table 1 are the same for all kilns as the exit temperature of clinker is assumed to be equal, i.e., 100°C.

In order to improve the efficiency of cement kiln, the following measures to reduce heat losses can be considered:

(1) By decreasing the amount and temperature of exit gas to reduce exit gas loss.

(2) By increasing the specific kiln output or by other measures to reduce radiation loss.

(3) By decreasing the water content of slurry for wet kiln to reduce the heat requirement of evaporation.

(4) By utilizing the cooler vent air to dry coal, or by decreasing cooling air to some extent to reduce vent air loss. However, decreasing the amount of cooling air will raise the exit clinker temperature and clinker loss increased. Therefore, there must be a compromise between them. In general, the vent air loss is higher than the clinker loss.

In addition to the above mentioned measures which are dealing with heat losses, some other measures, such as, improving the burnability of raw meal, lowering the heat of formation of clinker, etc., can be taken to lower the total heat consumption. Although they can not help to improve the kiln efficiency, they do help to increase the output, and the radiation loss can be reduced somewhat. Therefore, it is worthwhile to call attention in view of energy saving.

With regard to improve the heat economy of cement rotary kiln by improving kiln operation, problems on three different phases will be discussed in this paper. They are:

(1) Combustion process ——How can the heat be released from the fuel effectively?

(2) Heat transfer process——How can the released heat be transferred to the material promptly and efficiently?

(3) Thermo-chemical process——How can the reactions be proceeded rapidly during the burning of material?

The aboved mentioned problems constitute the entire thermal technology of cement rotary kiln, therefore they are the fundamentals for improving the heat economy in kiln operation. We are going to discuss them in that order, and to give some brief explanations about the experience which have been gained in China.

II. Combustion Process

Whatever the kiln type may be, the heat loss due to exit gas is the major item among the losses. It amounts to 15-30% of the total heat consumption. In order to reduce the exit gas loss, it is important to supply a correct amount of air for combustion. Air supply either more or less than necessary will cause heat loss. When air supply is more than necessary, too much excess air will be present in the kiln. If this excess air comes from clinker cooler, the heat loss will not be very serious since it recovers some sensible heat from clinker, and reduces vent air loss of cooler. However, it increases the amount of exit gas, and the exit gas loss will be raised as the kiln exit gas temperature is higher than the cooler vent air temperature. If the excess air originates from air leakage, especially the leakage at the lower end kiln hood, the situation will be much more serious. An the false air from kiln hood will not only lower the flame temperature, but also displace the secondary air from cooler. It is obvious that this false air will raise both vent air loss of cooler and exit gas loss of kiln.

Martin (1) had calculated the fuel loss in heating the excess air as percentage of total fuel burnt in the kiln, as shown in Table 2, when O_2 content in exit gas exceeds 2%, the fuel loss becomes significant, it will exceed 1% of the total fuel burnt.

On the other hand, when the air supply is less than necessary,

Table 2. Tons of coal consumed in heating excess air per 100 tons of coal burnt in the kiln, standard coal: 7000 kcal/kg coal

O_2 in comb'n. gas, vol.%	Excess air, vol.%	% of fuel loss to total fuel consumption		
		238°C(460°F)	404°C(760°F)	516°C(960°F)
0.5	2.3	0.1919	0.3353	0.4314
1	4.8	0.3972	0.6942	0.8925
2	10.2	0.8512	1.490	1.916
3	16.3	1.377	2.410	3.1[illegible]0
5	31.5	2.724	4.867	6.130
7	52.9	4.685	8.198	10.55

it will cause even more heat loss. Defficiency of combustion air will cause incomplete combustion and produce carbon monoxide. The heat generated from carbon burnt to CO will be only 30% of the total heat that could be generated when combustion is complete. The escape of CO to the exit gas means the escape of valuable fuel. Every 0.1% of CO added to the exit gas corresponds to 0.6% of fuel loss.

Therefore, the air supply should neither be too much in excess nor be too less. It must secure a complete combustion in the kiln, and must keep the exit gas to a minimum as well.

There are almost 25 milliom tons of cement produced by rotary kiln in China, and mostly using pulverised coal as fuel. About 8 million tons of coal consumed annually. To reduce coal consumption in kiln operation is quite a task in China so far as energy saving is concerned. That is why we should study the conditions of combustion and try to find out whether we can exert influence on them.

According to our experience, to accelerate the combustion rate and to make full use of combusting space in the kiln are the points worthwhile to be emphasized in kiln operation. In other words, to make efforts in establishing a long high-temperature burning zone is considered to be a precondition for raising kiln output and lowering heat consumption.

The combustion process of pulverised coal consists of three stages: (1) the heating and ignition of coal particles; (2) the volatilization and combustion of volatile matter; (3) the combustion of coke residue.

During the heating and ignition stage, the moisture remained in coal particle will first be expelled out, and the coal particle itself will be heated up. The ignition temperature is different with different kinds of coal. For lignite, it is 200-300°C; for anthracite, 450-600°C. Bituminous coal will have an ignition temperature inbetween. When the surface temperature of coal particle reaches ignition temperature, the reaction rate will attain certain value which is capable to maintain a continuous combustion. To reach the ignition temperature, a certain period of time is required, it is called ignition time. This time is determined not only by the conditions of coal itself, but also by the ambient conditions. That means both the coal and the combustion air have to be heated to ignition temperature. The amount of heat required for heating air is much larger than that required for cal. At 10% excess air, the heating of the combustion air requires nearly 90%, whereas the heating of pulverised coal requres only about 10% of the heat which is necessary for ignition. In case of cement rotary kiln, the ignition time is about 0.5 seconds(2).

The time required for volatilization and combustion of volatile matter is also instantaneous. The volatile matter of coal consists mainly of hydrocarbons. The temperature required for volatilization is generally lower than ignition temperature. Therefore, the volatilization sometimes takes place before ignition, and it proceeds simultaneously with the first stage. During the expelling of volatile matter, the size of coal particles will expand 2-8 times larger. Expansion increases the surface area and tends to reduce the time required for this stage of combustion. The heat generated during this stage is sufficient to secure a high temperature which is required for the combustion of coke in the next stage.

The time required for combustion of coke residue is much longer than the two preceding stages. It determines the rate of combustion process. The duration of this stage depends on many factors. As far as the coal itself is concerned, it depends on the type and the particle size of coal. For a given coal, the particle size is the decisive factor. Small particle burns very fast, while large particle requires a longer time to burn out. Therefore, the latter determines the time required for a complete combustion. Besides, the faster the combustion gas are removed and replaced by fresh air, the faster the coal particles will burn. To fulfill this requirement, a well mixing and a high relative velocity between the combustion air and coal particles are necessary.

In general, in case of rotary kiln, 0.1-0.3 seconds are reqired for combustion process. But there will be a few coke particles remain unburnt. Further eliminating the unburnt carbon takes quite a long time. According to our experience, to accelerate the combustion rate (to shorten the combustion time) is very important in kiln operation. The rate of combustion can be testified by flame temperature and flame length. The faster the combustion is, the more concentrate the heat will release, and the higher the flame temperature will be. It is advisable to raise the flame temperature as high as possible. Because a higher flame temperature will not only be beneficial to cement quality, but also to heat transfer. It allows a shorter retention time of the material in the burning zone, and therefore a higher kiln output could be expected. Anselm (3) stated that a 10°C higher temperature will raise the production at least 1%. Of course, there is a limit on accelerating the combustion rate. The service life of the kiln lining must be considered in the first place. To protect the lining from local extreme temperature which may be originated from a very intense flame is advisable. The second point is to prevent a back fire which is caused by a very fast ignition by which the coal ignites as soon as it leaves the nozzle or even in the burner pipe. This will cause big damage which is not permissible for safety sake.

The acceleration of combustion rate means earlier ignition and more concentrate heat releasing. This results in shortening the flame length. It is necessary to distinguish two different significations about the flame length: the total flame length and the combusting flame length (7). The former denotes the distance between the nozzle and the end of flame, while the latter denotes the distance between the point where the ignition starts and the end of flame. In other words, the difference between the two significations is whether the dark cone is considered to be a part of flame (Fig. 1). The concept of "the end of flame" means the end of the bright flame. In fact, the bright flame is ended after 90% of coal particles have been burnt out. Therefore, it is different with the concept of "complete burn out".

Every kiln has a space for combustion. This space for rotary kiln is the burning zone. The amount of heat that could be released during combustion is called the heat release capacity of kiln. This quantity (heat release capacity) divided by the volume of burning zone is called the thermal intensity of burning zone. Shortening the flame means that the heat will be released in a shorter distance, so the thermal intensity

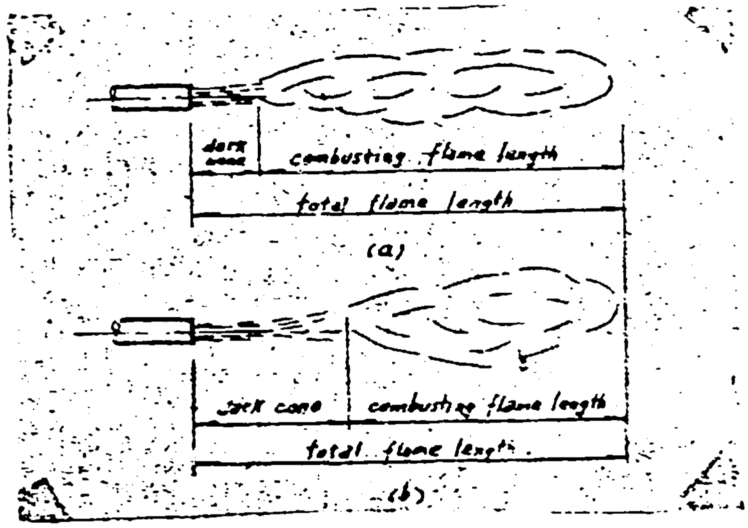


Fig. 1 Length of flame

of burning zone is raised. In other words, if the heat release capacity remains constant, there must be a saving of combusting space when a higher thermal intensity is obtained. In this case, heat is concentrated at a space where is in urgent need for clinker burning, and the effective length of kiln available for preheating the raw meal is lengthened resulting from the saving of combusting space. Then, exit gas temperature is lowered, and heat loss due to exit gas reduced. On the other hand, saving of combusting space creates an opportunity to make full use of this space. It enables the operator to raise the heat release capacity or the kiln output further. Then the burning zone is lengthened but it is based on a higher temperature. In short, a long high-temperature burning zone thus established will perform high quality, high output, and low consumption in kiln operation. This is the ideal that our kiln operators have long striven for.

In following paragraphs, the influences of pulverised coal, combustion air, and kiln draft on combustion rate, or on flame, will be discussed individually.

(1) Pulverised coal

Duda (4) pointed out, to insure an economic kiln operation, the heating value of coal should be about 7000 kcal/kg coal. Coal with a lower heating value will increase the specific heat consumption and decrease simutaneously the specific kiln output. The reason is that a higher flame temperature can be obtained more easily with a coal of higher heating value, and the amount of combustion gas produced per 1000 kcal of heat released is less. However, if the combustion air could be proheated to a higher temperature, it is possible to use a coal with somewhat lower heating value. Not a few cement plants in this country have to use the local coal with inferior quality. In order to insure an economic kiln operation, we suggest that the low heating value of coal used in cement industry should not be less than 5000 kcal/kg coal.

The effect of volatile matter of coal on flame is obvious. Bituminous coal with high volatile matter will ignite close to burner nozzle, and produce a long flame; on the contrary, lean coal with low volatile matter will ignite at a distance far from the nozzle, but the flame is more concentrate (refer to Fig. 1a and 1b). The difference in ignition time is due to the ignition temperature increases with decreasing volatile matter content. In addition, for coal with high volatile matter, the heat is generated in a longer distance as volatile matter will burn earlier than coke; while for lean coal, almost 80% of heat is released in a short distance. For the latter case, the flame is concentrate, sometimes causing local extreme temperature. Therefore, it is necessary to have a coal with suitable volatile matter for kiln operation. A coal with 18-30% volatile matter is generally adopted in our cement plants. Beyond this range, it might be compensated by regulating the fineness of grinding of pulverised coal.

The effect of moisture content of coal on combustion is also apparent.

A little moisture remained in coal will be helpful to ignition. The presence of some moisture will promote the reaction of carbon with oxygen, and raise the radiating power of flame. Therefore, coal should not be overdried, 1-1.5% moisture remained in the coal is desirable. However, too high moisture content in coal will cause adverse influence. It will lower the flame temperature, lengthen the flame, and raise the exit temperature. Anselm stated that 1% moisture in fuel will lower the flame temperature about 10-20°C, and cause 2-4% more exit gas loss. He also pointed out, the effect of moisture content on temperature is twice as much as compared with the ash content in the pulverised coal.

The finer the pulverised coal is, the faster the combustion rate will be. Fineness of coal will exert more influence on combustion rate than the volatile matter. Gumz (4) had offered the relation between particle size of coal and burning time, as shown in Fig. 2a. The curves show the burning time required for coal particle with diameter from 20 to 500 micron at the temperature of 900 & 1500°C. It shows that, for the particle diameter under 60 micron, burning time required is 0.1-0.3 seconds; while for particle with 500 micron, it requires 10 seconds, Spaldin (5) gave similar curves as shown in Fig. 2b, which shows the burning time required under different 02 concentrations. The fineness of pulverised coal required for rotary kiln can be calculated according to the ash content and volatile matter content of coal as follows:

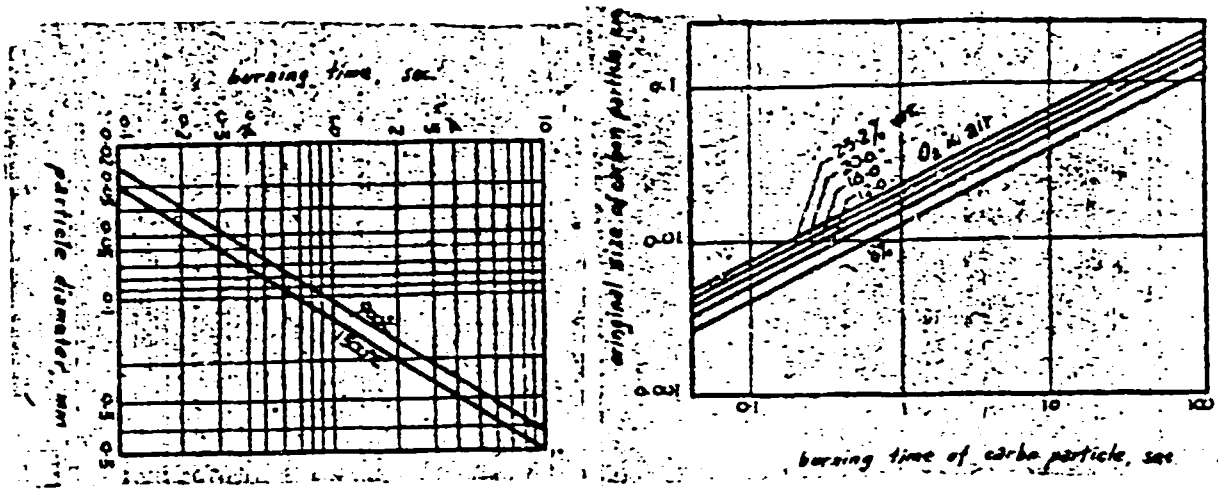
Fig. 2. Relation between particle size of coal and burning time

$$R90 \leqq (0.9 - 0.001A)(4 + 0.5V)$$

Where, R---fineness of pulverised coal, % retaining on 4900 mesh sieve;

A---ash content of coal, %;

V---volatile matter content of coal, %.



(a) after Gumz (b) after Spaldin

(2) Combustion air

In order to accelerate the combustion, it is necessary to have a well mixing bewteen combustion air and coal particles; especially between primary air and pulverised coal.

The pulverised coal is injected into the kiln through burner pipe by means of primary air; and the secondary air is first preheated in the clinker cooler and then introduced to kiln. The funtions of primary air are: (1) to transport the coal dust into the kiln; (2) to encircle the coal particle with air so that it will ignite conveniently after leaving the nozzle. One can use mechanical method to intensify the mixing, e.g., to insert spiral blades inside the burner pipe to produce a whirlwind on coal-air mixture. Another method is to increase the ratio of primary air to coal. Thus the concentration of coal dust in the mixture will be lowered and the mixing improved.

Nevertheless, the percentage of primary air may not be too high or otherwise the amount of secondary air will be displaced too much which will influence the cooling of clinker and the efficiency of cooler. That is to say, the heat losses due to cooler vent air and clinker will be increased by increasing primary air. Besides, since the temperature of primary air is much lower than secondary air, too much primary air will also be detrimental to combustion. In general, the percentage of primary air is about 25% of total combustion air. Some Lepol kilns with rotary cooler in China use only 15% primary air. This is due to the heat consumption of Lepol kiln is low and the total combustion air required is less. It is necessary to keep a low percentage of primary air to insure sufficient secondary air passing through the cooler. Someone suggests that the amount of primary air could be as much as the required for burning volatile matter. That means the percentage of primary air is roughly equal to the percentage of volatile matter of coal. This can be used for quick estimate.

The velocity of the coal-air mixture in the nozzle has a significant influence on the flame length. Generally, the higher is the velocity in the nozzle, the longer is the total flame length. This is due to the fact that the unburnt coal-air mixture with higher velocity tends to produce a longer reaction zone. However, Dersnah (6) observed 14 rotary kilns and pointed out that in the range of 15-40 m/sec (3000-8000 ft/min), the flame length will be lengthened with increasing velocity in the nozzle. Beyond this upper limit, it will influence the flame

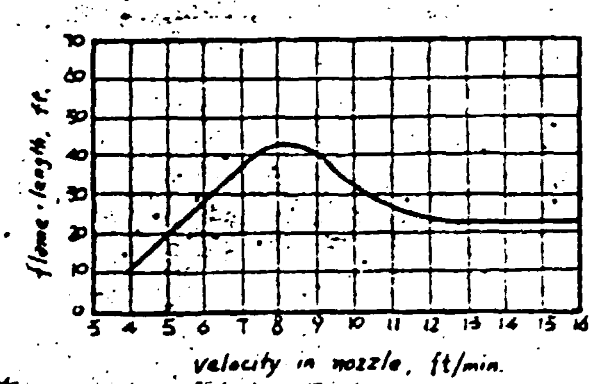


Fig. 3 Relation between the flame length and velocity in nozzle

length adversely, as shown in Fig. 3. He stated that whether the flame length is shortened or lengthened mainly depends upon the original velocity in the nozzle. When the velocity is already normal (say, 40 m/sec), the flame will be shortened and intensified by increasing velocity in the nozzle.

Neither too high nor too low a velocity in the nozzle will be helpful to kiln operation. If the velocity is too high beyond certain limit, it will shift the flame farther from the nozzle and the burning zone will be shifted accordingly. On the contrary, if it is too low, the flame will be too close to the nozzle. To prevent this, the velocity in the nozzle must be higher than diffusive velocity, i.e., not less than 20-25 m/sec. And the distance from nozzle to bright flame must be kept at least 0.25 m. The velocity in nozzle used in our cement plants is usually in the range of 40-80 m/sec. The value used for designing burner nozzle is 50-70 m/sec.

The velocity in the nozzle is also related to kiln diameter. A large diameter kiln requires higher velocity in nozzle. Fig. 4 is suggested by Duda who stated that these nozzle velocities result in optimal flame shapes, and cause favorable conditions for heat exchange between the flame and kiln feed.

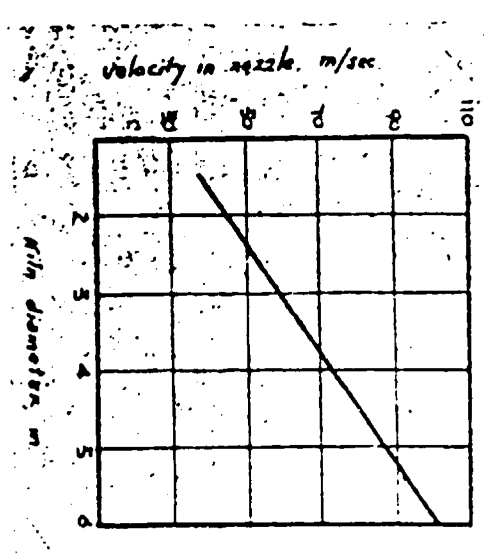


Fig. 4. Relation between the velocity in nozzle and kiln diameter

The temperature of combustion air will also influence the flame. The primary air is not preheated generally. But if the exit gas from coal mill is used as primary air, it will have a temperature about 70°C. The temperature of secondary air is usually high. It is higher than 800°C when preheated by grate cooler. However, most of our rotary kilns use secondary air with temperature not higher than 600°C. To raise the secondary air temperature will undoubtedly raise the flame temperature, and also be helpful to shorten the dark cone. But its influence on bright flame is not significant. The reason is that increasing of air temperature does increase the activity of O_2 molecules, but it is counter balanced by decreasing of air density (6).

(3) Kiln draft

Kiln draft condition will exert strong influence on flame. Sufficient draft must be kept at the back end of kiln in order to remove the combustion gas and the gas produced from calcining of raw meal promptly. In the meantime, the total amount of combustion air inside the kiln is also controlled by kiln draft. If the speed of draft fan is increased without increasing the coal feed, the amount of combustion air is increased, and vice versa.

As mentioned before, the ratio of combustion air to coal must be kept normal, neither too high nor too low. In order to insure complete combustion of pulverised coal, certain amount of excess air is necessary. In general, 5-15% excess air is maintained in the kiln by regulating the draft fan, it corresponding to an O_2 content 1-2 % in exit gas*.

* This excess air is based on the kiln exit gas, and the value is different with that in Table 2 which is based on combustion gas.

However, this excess air must come from cooler, and the false air from various parts of kiln system must be eliminated as far as possible. There should be no CO in exit gas.

To speed up draft fan will increase the amount of combustion air and facilitate combustion. But, too big draft will lengthen the flame and lower the flame temperature. Sometimes it will shift the various reaction zones insite the kiln, destroy the normal temperature distribution, and disturb the kiln operation. The exit gas temperature will then be raised and the heat loss due to exit gas increased.

If the kiln draft is seriously defficient, the flame length will also be lengthened. This is due to the defficiency of oxygen in the burning zone, the unburnt coal particles will proceed to the back end to seek for oxygen for combustion. The unburnt coal powder even get into the electrofilter to ignite there resulting in explosive damage.

In general, the kiln draft must be kept in conformity with the output. Once regulated to normal, don't change it too often. Even when a changing of coal is made, the kiln draft must not be changed too much in order to keep the flame and the temperature distribution inside the kiln more stable.

III. Heat transfer process

As mentioned in the above paragraphs, a high-temperature long flame should be maintained during combustion in order to raise the heat release capacity of the kiln. However, a rotary kiln is not only a combustion furnace, but also a process equipment which is responsible for burning clinker. After the liberation of large amount of heat, it must be transferred promptly and effectively to the kiln feed to produce cement clinker. To promote the heat transfer efficiency of various zones of kiln will secure the achievement of this fundamental task. The heat transfer process in rotary kiln is a complex and varied one. The high temperature part of the kiln, i.e., the sintering zone and the calcining zone, is merely a hollow pipe. The main heat source is the hot gas with solid particles. It transmits heat to the upper surface of kiln feed and to the exposed part of kiln lining simultaneously by radiation and convection. The heat absorbed by lining will be reflected back to the gas and through gas to the upper surface of feed by radiation. During the revolving of kiln, this exposed part of lining will then contact with the lower surface of feed and give the stored heat to the feed by direct conduction. The kiln feed itself will also conduct heat transfer from surface particles to interior by convection and conduction during revolving. In the low temperature part of the kiln, i.e., the drying zone and the preheating zone, various kinds of heat exchangers are inserted inside the kiln. Heat transfer in this part takes place mainly by convection and conduction. Since the temperature here is relatively low, heat transfer by radiation is not significant. Therefore, in the high temperature part of kiln, radiation plays the leading role; while in the low temperature part, convection and conduction get the first place.

(1) Heat transfer in high temperature part

To raise the gas temperature is an effective measure to promote the heat transfer in the high temperature part of kiln, since radiation is proportional to the 3.5th power of gas temperature. The sintering zone of kiln is a zone with the highest temperature, but the amount of heat transmitted is almost zero. The only requirement to this zone is to keep the material under high temperature with sufficient time in order to accomplish the lime absorbing reaction. On the contrary, the temperature of calcining zone is relatively lower than that of sintering zone, but the amount of heat to be absorbed is the most. Therefore, in view of heat transfer, this is the main reaction zone in cement kiln. To raise the gas temperature will accelerate the heat transfer and decrease the retention time required in both zones.

The length of calcining zone is generally about 40% of the total length of kiln (exclude the drying zone of wet kiln). This is necessary as the decomposition of calcium carbonate takes long time. Therefore, raising gas temperature is even more important for calcining zone. It enables the reaction taking place in a shorter distance and the "surge of unburnt raw meal" into the sintering zone can thus be avoided. It should be mentioned that the undecomposed raw meal surging into sintering zone is the main course that makes the kiln operation unstable.

The heat transfer process in calcining zone is by no means efficient. The main reason for this is the contact surface between material and gas is too limited and the heat absorption for calcining can not be proceeded rapidly. The precalcining technology which has been developed by Japanese cementists recently is to shift the calcining reaction to a calciner outside the rotary kiln where the reaction taking place under suspensing condition. The time required for decomposition originally amounting to tens of minutes is reduced to only a few seconds. The degree of calcination of raw meal after precalcining is very stable, the kiln operation is thus greatly stabilized, and the specific output greatly increased. This manifests itself that changing the type of heat transfer will significantly accelerate the heat transfer rate in calcining zone.

The kiln revolution is another important factor which exerts noteworthy influence on heat transfer process. The faster the kiln revolves, the more rolling action will give to the material, and, in turn, the more new surfaces of feed will be exposed to hot gas. In the meantime, to speed up the revolution will even out the temperature difference on the cross-section of material segment, and the surface temperature of the segment is lowered.

This is important especially to the lower surface which is stationary for a moment in contact with kiln lining during revolving, and the temperature raised rapidly. Lowering this temperature will allow more heat to be absorbed by the material. Besides, fast running of kiln will also facilitate the escaping of CO_2 from the material. All of these are the advantages for fast running of kiln. However, the retention time of material in various zones must be kept long enough when speeding up a kiln.

The experience of fast running of kiln had been exchanged between Chinese cement plants (9). It was done since some cement plants had operated their kilns with too low a speed (e.g., one kiln with only 0.37RPM) at that time. After that, the revolutions of most kilns had been raised to more than 1 RPM. But, some plants had gone to another extremity. As the kiln ran too fast, the poor prepared raw meal surged to sintering aone and one had to slow down the kiln again, thus caused the kiln operation seriously unstable. In order to correct this misleading, it had been emphasized that the important thing was to stabilize the kiln speed instead of merely pursuing a high value of RPM, i.e., to keep the slow-down to minimum. For individual kiln, the first thing is to find out a normal kiln speed based on its concrete conditions, such as, slop of kiln, raw meal used, and maintenance condition, etc.. Once the normal speed has been ascertained and stabilized, the necessity and possibility of further speed up the kiln could then be considered.

The kiln revolution has a very close relation to its slop. The slop is a fixed factor for an existing kiln, but this already fixed condition must be considered previously in finding the normal kiln revolution. The influence of kiln slop is contrary to that of kiln revolution. When retention time of material is kept constant, kiln revolution is inversely proportional to its slop. In order to keep the distance travelled by the material per revolution within certain limit, it is necessary to have a larger slop for smaller diameter kiln, and a smaller slop for larger one.

Another factor which will influence heat transfer is the degree of filling in rotary kiln. It is obvious that too small a degree of filling will be unfavorable to heat transfer, because both contact surfaces between the gas and material, and the material and kiln lining are diminished. However, if the kiln is half filled with the material, it will be unfavorable to heat transfer either. Therefore, there must be an optimum value of degree of filling under certain gas temperature. Gygi (14) had calculated this value based on measured data, and stated that 20% degree of filling will be the best figure for calcining zone with gas temperature 800-1500°C. In this case, 1/3 of the heat generated from gas will be transferred directly to the material, and 2/3 will be transferred indirectly by the kiln lining. He also stated that a range of 15-30% of degree of filling will be acceptable as the shape of the curve showed a horizonal part.

The actual value of degree of filling of most kilns is smaller than that is calculated by Gygi. As the material undergoes physico-chemical reactions in the kiln, the values for different zones are different. It lies in the range of 7-3%, and 10% in average generally. The optimum value of degree of filling is probably different with different kilns, and it must be determined in connection with the length, slop and revolution of the kiln.

Feng (10) had introduced an example about tests which had been done on a ∅3x75 m kiln. The tests were conducted by operating the kiln with variable slop, revolution and degree of filling. The results obtained are shown in Table 3. After 19 tests, the conclusion was: with 12% degree of filling, 165-170 minutes of retention time, and 14.3 t/h output, the quality of clinker was the best (No. 11, 12, 13 in Table 3). When the degree of filling was raised to 15%, ring formation ocurred; when it is lowered to 10%, the output was too low, and the coating on the lining was poor.

The tests shown in Table 3 are of course only for reference, as neither two kilns will have entirely same conditions, nor every kiln is capable to be allowed to carry out such tests. But one can see the general relationship between the slop, revolution and degree of filling of kiln, and also the output and quality of clinker from these tests. It is worthwhile to mention that, as the kiln feed is synchronized with the revolution, to increase the revolution only will not change the degree of filling but the output, so long as the slop is kept constant. This can be seen from the figures shown in Table 3. If one wants to change the degree of filling, the ratio of kiln feed to revolution should be changed. Someone had suggested so called "thin material with rapid burning" method as a supplement to the fast running of kiln. The meaning of this suggestion is to speed up the kiln without raising the output; this is actually to decrease the degree of filling. In our opinion, the so called "thin" or "thick" is merely relative, it depends on whether the original amount of feed in the kiln is "too thin" or "too thick"; and the problem is still one which looks for an optimum degree of filling in the kiln.

Table 3. Relation of slop, rev'n. & deg. of filling on ∅3 x 75 m kiln

No.	Slop, %	Rev'n., RPM	Output t/h	Ret'n.Time min	Deg. of fill'g.%	Remarks
1	3.5	0.7	11.1	218	12.2	too high liter wt.
2	3.5	0.8	12.7	191	12.2	"
3	3.5	0.9	14.3	170	12.2	medium liter wt.
4	3.5	1.0	15.8	153	12.2	too low liter wt.
5	3.5	1.1	17.4	139	12.2	"
6	4	0.7	12.5	190	11.9	
7	4	0.8	14.2	166	11.9	
8	4	0.9	16.0	147	11.9	poor qual'y clinker
9	4	1.0	17.8	132	11.9	"
10	4	1.1	19.6	121	11.9	"
11	3	1.04	14.3	170	12.2	
12	3.5	0.9	14.3	170	12.2	
13	4	0.8	14.2	166	11.9	
14	3.5	0.9	11.7	170	10.0	both coating and output are poor
15	3.5	0.9	14.3	170	12.2	
16	3.5	0.9	17.4	170	15.0	ring formation
17	3.5	0.8	14.3	191	13.7	
18	3.5	0.9	14.3	170	12.2	
19	3.5	1.0	14.3	153	11.0	poor qual'y clinker

(2) Heat transfer in low temperature part

In the low temperature part of kiln, i.e., in drying zone and preheating zone, the only method for accelerating the rate of heat transfer is to increase the contact surface between gas and material. As the heat transfer under low temperature is carried out mainly by convection and conduction, the magnitude of contact surface plays an essential role. This is the point why the heat consumption of the old type dry kiln is so high. The limited contact surface between gas and material in such kiln results in very high exit gas temperature; and quite an amount of heat having not yet been absorbed escapes as waste heat from the kiln. For modern preheater kiln and Lepol kiln, a preheater is used instead of the hollow pipe for the low temperature part of kiln. It enables much more intimate contact between gas and material than the old type dry kiln, and lowers the exit gas temperature a great lot. The efficiency is thus greatly improved.

The heat efficiency of Lepol kiln is comparable with that of suspension preheater kiln. It was this type of kiln that had improved the efficiency of cement kiln for the first time based on the principle of increasing contact surface in the low temperature part of kiln. Therefore, we may say that Lepol kiln is the pioneer of suspension preheater kiln. The main disadvantage of Lepol kiln is the prerequisite on nodulizing the raw meal. Nodulizing not only increases the moisture content of kiln feed, but also effects its wide adaptability to various raw materials. Nodulizing also requires more handling facilities for raw meal and therefore complicates the operation of kiln system.

According to our experience in operating a Lepol kiln, the draft condition of Lepol grate will influence greatly the output. Draft condition not only depends on the plasticity of raw mix and thereby the quality of nodules, but also the configuration of feed bin and the height of the falling path ahead of the Lepol grate. Even though the quality of nodules is acceptable, a better draft condition still can not be secured if the nodules have been compacted to each other inside the bin, or broken when dropping to the grate.

Fig. 5(15) shows the reconstruction of a feed bin in Xiaotun Cement Plant. The pressure drop accross the nodule bed had been reduced significantly after the reconstruction, and the output had been raised. The nodule size for Lepol grate in this plant is about 80% within the range of 10-20 mm.

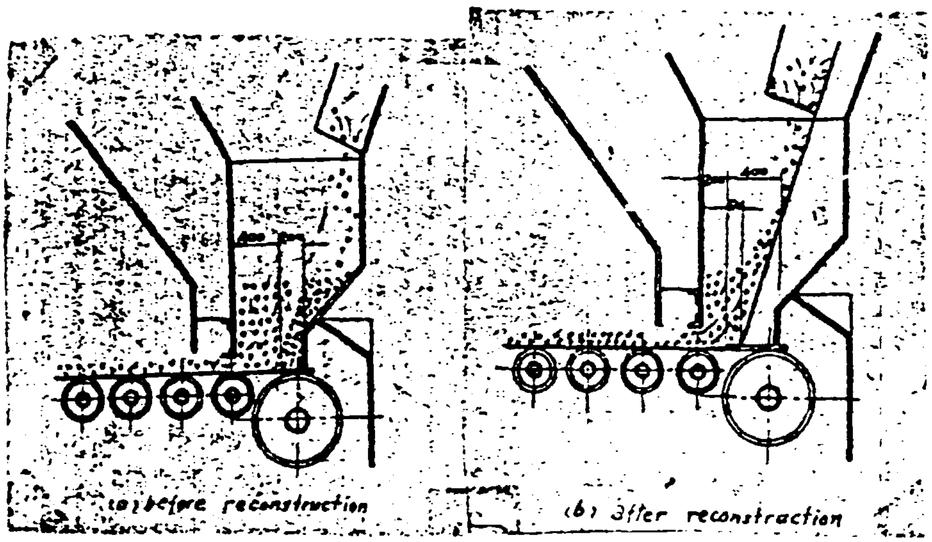


Fig. 5 Improving of feed bin for Lepol grate

Heat required for water evaporation is tremendous for wet kiln. Heat transfer in the drying zone is carried out mainly by chain system. To raise the density of chain curtain* to some extent will promote the rate of heat transfer in chain section. The average density of chain system in wet kiln of China is generally 3-4 m^2/m^2. Some cement plants have raised the figure to 4-4.5 m^2/m^2 and more giving good results.

Insertion of heat exchanger is a measure to promote the heat transfer in preheating zone. Not a few long wet kilns use cellular metallic heat exchanger at the outlet of chain system to increase the contact surface between gas and material. This exchanger is made of common steel plate and it will only stand for a temperature about 400°C. If it is intended to insert the exchanger at a location of higher temperature, it must be made of heat resisting steel. Cellular exchanger increases the draft loss;

*The density of chain curtain is defined as the ratio of total surface area of chain links to that of the lining of drying zone where the chain system is installed.

and the kiln dust is increased when draft fan is speed up to overcome this resistance. Besides, attention should be paid to the moisture content of material outgoing from chain zone. If the moisture content is high, the material will stick on the cellular plate. Therefore, it is not used widely now.

Some dry cement plants also had used fire brick cellular heat exchanger in preheating zone. This exchanger diminished the cross-sectional area of kiln by 25%, and increased the hydraulic resistance significantly. Jinxi (21) Cement Plant had used this exchanger and measured the draft loss. The draft in the kiln back end after insertion of the exchanger is twice as high as before. Since the draft fan is speed up, the raw meal consumption is raised 7.5%, and heat loss due to exit gas raised 21%.

Another type of heat exchanger is called screen type heat exchanger. It is a kind of metallic lifting bars placed between the lining bricks. The mushroom type bar covers the lining surface and shoots out about 100 mm above the lining. It looks like screens inside the kiln so it is called screen type heat exchanger in this country. The function of this exchanger that differs from cellular type is : the heat conductivity of lining surface is improved in addition to the lifting action which increasing the contact surface. Benxi Cement Plant (22) had reported a 3% output increase by using this exchanger.

In order to decrease the radiation loss from the kiln shell, some plants use insulating bricks made of kieselguhr between lining and shell in calcining zone. Generally it lowers the surface temperature of shell about 40-50°C. Heat loss is reduced about 40 kcal/kg clinker.

Most of our cement plants use water spray cooling system on kiln shell of burning zone. The purpose of water cooling is not for reducing radiation loss, but for protecting the coating. The experience gained for many years confirm its effectiveness. Neither corrosion nor caking on kiln shell has been observed. The water amount must be enough to wet the whole surface and no vaporization is allowed. It can be calculated according to formula: $Q = 4.3D_0^2$ t/h (where D_0 is the outside diameter of kiln shell). We have no experience on air cooling system.

IV. Thermo-chemical process

In order to match with the accelerated combustion in the kiln, it is necessary to accelerate the thermo-chemical reaction as well as the acceleration of heat transfer. Several measures can be taken, they are: (1) improve the burnability of raw meal; (2) use raw materials which have been pre-calcined; (3) fuel to be added to the raw meal to promote preheating; (4) decrease the water content of slurry, etc..

Raushenfels (27) stated that the burnability of raw meal is related to several factors: fineness of grinding, homogeneity, lime standard, silica modulus, liquid phase (especially ferric oxide), etc..He further stated that, with different type and crystal size of silicate components in raw meal, a good burnability could be obtained from a meal with high silica modulus.

The first thing to be considered to improve the burnability of raw meal is the fineness of grinding. Before the raw meal entering sintering zone, solid state reaction takes place inside the kiln. It seems probable that the solid state reaction can be accelerated by increasing fineness which will increase the surface area of reacting particles. However, it is not the case as both limestone and clay particles in raw meal undergo decomposition before they react to each other. CO_2 expelled from limestone particle during calcining makes it porous and increases its surface area. In the meantime, amorphous SiO_2 and Al_2O_3 which are formed in decomposed clay are surface active in solid state reaction. Therefore, it is doubtful whether a very high fineness of grinding is necessary. A higher fineness should be obtained if the raw meal contains certain amount of quartz, however.

Bogue (23) had carried out a burning test at 1350°C and stated that the particle size of limestone and alumina gives only little influence on burnability of raw meal, while the size of quartz particle gives significant influence. Heilmann (24) had investigated the influence of the fineness of raw meal on its burnability. He pointed out, the percentage of coarse quartz particles larger than 200 micron should not exceed 0.5% in a raw meal with 95% LSF; while 5% can be allowed for coarse limestone particles larger than 150 micron. Even coarser particles of limestone can be tolerated if silicates instead of silica are contained therein.

He further stated that the size distribution of fine particles smaller than 90 micron gives little influence on burnability, but certain amount of finer particles, such as 35% of 15 micron particle, is necessary to secure a good burnability. These requirements can be fulfilled by ordinary grinding circuits, either open circuit or close circuit.

Better blending of raw meal will improve its homogeneity. It provides more chance for the particles of limestome and clay to contact each other and therefore benefits the solid state reaction.

The next thing to be considered to improve the burnability is to alter the chemical composition of raw meal. One should not lower the lime standard as it will lower the early strength of cement. But the alumina modulus P (Al_2O_3/Fe_2O_3) can be altered which will influence the amount and viscosity of liquid phase. The liquid phase plays an importment role in clinker formation eventually.

Bogue stated that the fluxing action is maximum when the value of C_4AF/C_3A

ratio lies in the range of 1.5-20 (corresponding to Al_2O_3/Fe_2O_3 = 1.2-1.4). Lea and Parker (25) had determined the eutectic temperature of ternary system C_3S-C_2S-C_3A-C_4AF being 1338°C, and the corresponding liquid phase has an alumina modulus P=1.38. They stated that, at this temperature, Fe_2O_3 will enter into liquid phase completely while a part of Al_2O_3 still remain in solid when P>1.38. In this case, the amount of liquid depends on Fe_2O_3 content. If P<1.38, Al_2O_3 will enter into liquid completely while a part of Fe_2O_3 remains in solid. Swayze (23) (28) studied further the ternary system by adding 5% MgO to the system. He modified the value of P of eutectic composition of liquid to be 1.63. Toropov (26) considered that the temperature at which both Al_2O_3 and Fe_2O_3 enter into liquid completely depends on the value of P. For most cement raw meal, this temperature is in the range of 1340-1400°C. Since it is common practice that both Al_2O_3 and Fe_2O_3 are required to enter into liquid completely, therefore, the sintering temperature can be lowered by altering P. Toropov further pointed out, raising Fe_2O_3 content of raw meal will greatly lower the viscosity of liquid phase and promote the diffusive rate of reacting particles. Most cement plants in China favor a clinker with alumina modulus below 1.38. This is somewhat different with cement clinker abroad. The kiln operators in this country used to burn raw meal with such composition, but they haven't got any definite idea how alumina modulus influence the kiln operation.

Some cement plants in China had added mineralizers to raw meal in order to lower the temperature of liquid formation. Fluorspar (CaF_2) was used more often. It lowers the sintering temperature about 100-150°C, and lowers the viscosity of liquid phase simultaneously. The amount of fluorspar added should not be too much, generally 0.2-0.5% of clinker weight. It must be thoroughly mixed with raw meal. Too much fluorspar or an uneven distribution of fluorspar in raw meal will cause damage of lining in sintering zone or cause ring formation or formation of big lumps in the kiln. In addition to fluorspar, some industrial wastes, such as phospho-gypsum, fluro-gypsum, silico-fluorides ($MgSiF_6$ or Na_2SiF_6) have also been used in some plants. Our opinion is, only under such conditions that the lime standard of raw meal is very high, or a higher sintering temperature have to be maintained, the addition of mineralizer will then be necessary and beneficial.

Using lime or blast-furnace slag as raw material will decrease the heat of clinker formation and raise the kiln output. Using lime instead of limestone as raw material will greatly ease the kiln of its job as the decomposition of $CaCO_3$ takes place outside the kiln. Calcined limestone also eases grinding work and saves power for raw mill. In the meantime, the weight of calcined limestone is only about half as compared with raw stone, so a saving of handling cost results. These are the advantages for this process. On the other hand, it is difficult to keep the quality of lime constant, and the variation of degree of calcining causes trouble on kiln operation. The slaking property of lime also prevents it from using in wet kiln or Lepol kiln. Besides, as the limestone undergoes heat treatment twice in the process, the process is complicated and more heat is lost during manufacturing. Therefore, this process is only adopted in small cement plants where power supply is insufficient. It has not found its place in large plants.

Using blast-furnace slag instead of clay as raw material will raise the kiln output and lower the consumptions of raw meal and coal. It allows not only to utilize the industrial wastes, but also to save the agricultural land which otherwise must be excavated for supplying clay. Not a few dry process cement plants in China have adopted this material as raw material. Generally, the production have been raised 10-20%, and coal consumption lowered about 15%. Due to the ignition loss of slag-containing raw meal is lower than common raw meal, the consumption of meal is lowered about 10%. The quality of clinker is satisfactory (13). However, as slag possesses latent hydraulic property, it can't be used in wet process plant. Chongqing Cement Plant had tried to approach this problem by adding 0.075% $\pm$ 0.02 waste molasses to the slag-containing slurry. The slurry did not appear hardening until 18% slag was added. Slag can not be used in Lepol plant either as the plasticity is not as good as clay to give a good nodulizing.

Slag-containing raw meal can be used in wet process plant by feeding it dry to the middle part of kiln or by insufflating it to the burning zone from kiln hood. Huaxin Cement Plant (44) had insufflated a raw meal as 1:1 limestone-slag mixture to the burning zone in addition to the ordinary slurry fed to the back end of kiln. The amount of insufflation was about 5% of clinker weight. It was estimated that 0.5-1 t/h of output increase had been gained. Some wet process plants also use these methods for treatment of kiln dust which is collected from electrofilter.

Adding pulverised coal to raw meal or slurry to intensify the preheating of the latter had been investigated in some plants. The theoretical base of this process is, there is a limit in raising the thermal intensity of burning zone so the kiln output is also limited. If one can utilize the back end space of kiln for combustion, the total heat release capacity of kiln can thus be raised, and the production being raised accordingly. This idea is somewhat like the secondary firing which has currently been adopted in the preheater kiln. Jiangnan Cement Plant (wet plant) (34) had adopted so called black-slurry process and reported that no difficulty had been encountered in kiln operation. The output had been raised 4% with a slight reducing of coal consumption. Using sulfite alcoholic waste liquor (from paper mill) or other slurry diluents to decrease water content of slurry is an effective measure for wet process cement plant. Lowering the water content of slurry will raise kiln output and lower fuel consumption. Every 1% lowering in water content tends to save fuel consumption about 2%. Guanzhou Cement Plant (33) had added sulfite liquor 0.2% of slurry gaining a lowering in water content 3%. The output had been raised 6%, coal saved 3-6% and the time for slow running the kiln reduced 46%.

Most cement plants in China use ordinary fireclay brick (Al_2O_3 40%) for lining in burning zone. A few plants use high alumina brick (Al_2O_3 70%) or basic brick (magnesite or chrome-magnesite brick). This situation is unfavorable as far as raising flame temperature is concerned. Xiaotun Cement Plant (35) had adopted chrome-magnesite brick in burning zone, and reported that the service life of lining reached a record of 158 days. Then they used high density alumino-magnesite brick instead, the record further stepped to 182 days. However, most of our plants have no experience on basic brick. In order to cope with the requirement of raising flame temperature, a better coating and a careful maintaining of coating had been emphasized. "Long period safety running of rotary kiln" had been a slogan to call upon kiln operators to strive for it. Jiangnan Cement Plant (36) had set a best record in continuous running of kiln to 663 days. It is generally stressed that the temperature inside the kiln must be stable when start to coat the lining and no slow running of kiln should be allowed during this period. The chemical composition of raw meal for coating will be either normal or a slight reducing of $CaCO_3$ content. One plant had spreaded some iron cinder over the lining surface when start the coating, but most plants considered that is unnecessary. The time for coating the lining is generally 3 - 7 days.

V. Conclusion

Someone believes that there is contradiction between kiln output and heat consumption, i.e., to increase output will unavoidably increase the heat consumption. It is supposed that the burning zone will be lengthened as soon as the output is increased; this will certainly raise the exit gas temperature, and the heat consumption is raised accordingly. Based on this supposition, a question "Which one is required, a high production or a low consumption?" had been sometimes raised by kiln operator as if they are antagonistic each other and no compromise could be occur. However, in view of heat economy of cement rotary kiln, we need not only a higher production, but also a lower consumption. That is to say, a most economical production must be pursued in kiln operation. Weber (37) had studied this problem in detail and suggested a relationship between kiln output and heat consumption as shown in Fig. 6. From Fig. 6 we can see, when the output is below certain level, the heat consumption will be lowered with increasing production. When the output reaches certain level, the curve shows a horizontal part. Weber considered that the end of this horizontal part will be a point which denotes the most economical output. After this point, the heat consumption will be increased with increasing production. It is obvious that the contradiction will occur only when the most economical production has been exceeded.

Before the most economical production has been reached, the kiln is considered to possess production potential. In order to bring out the potentialities into full play, a proposal called "three-bigs and one-fast" was suggested for kiln operation by the industry in 1958. The proposal is, using big draft, big fire, big feed and fast running of kiln to raise the production with good quality of clinker. This proposal was put forward as a sum up cf experience which has be gained years before. As early as early fifties, some cement plants had promoted their production by speeding up the draft fan of kiln. For example, Shoudu Cement Plant had raised the output of four small rotary kilns, ∅2.4 x 40 m, from 4.5 t/h to 6.5 t/h by increasing the kiln draft. The increasing of production is 44%. About 1953, cement plants in Northeast China had exchanged their experience about long-flame and fast running operations and resulted in production increase. Later on, three operating experiences, namely, fast running of kiln, long period safety running of kiln, and water cooling on kiln shell, had been disseminated among cement plants all over the country. Then a national congress was held in 1956 to sum up the three experiences. In this congress, further requirements had been requested, such as, rational forcing of kiln, stabilizing the kiln speed, etc.. The operating technique of cement rotary kiln had thus been systematically advanced since then. We can realize that the "three-bigs and one-fast" proposal was really based on fruitful experience.

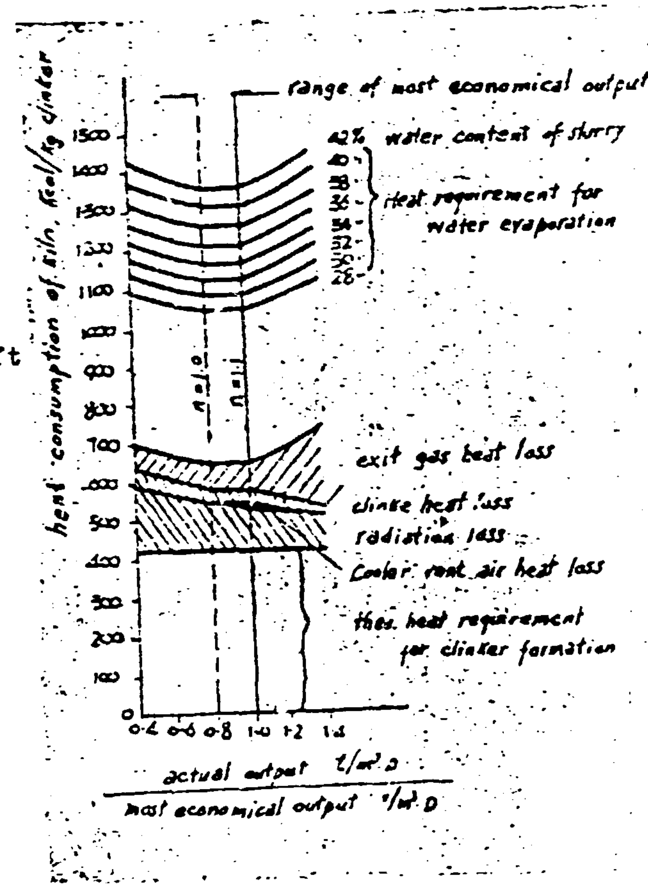


Fig. 6. Relation between the kiln output and heat consumption (Weber)

After long time practice, many cement plants had tapped the production potential of their kilns. But some of them had ignored the quality of clinker and also the heat economy. By to and fro adjustments, now most kiln operators are able to control the draft, fire, feed and speed in harmony, and pay attention also to lower the fuel consumption. It is possible for them to find out what is the most economical production in their kilns.

The actual meaning of "three-bigs and one-fast" proposal is to make good use of combusting space of kiln, or to make efforts in establishing a long high-temperature burning zone in the kiln so that the production can be promoted. We have gained some experience in this respect. However, this proposal tends to cause misunderstanding as it stresses only the raising of burning capacity, while the necessity of raising of preheating capacity to cope with the former has been overlocked. Therefore, it is advisable to properly arrange the interrelation between burning capacity and preheating capacity in operating a kiln. Or, we may say synonimously, to harmonize the relation between heat release capacity and heat transfer capacity is a basic problem for finding out the most economical production. Kiln operation based on integrated considerations of combustion, heat transfer and thermo-chemical processes will be helpful to gain more experience in improving the heat economy of cement rotary kiln.

Refferences

(Refer to Chinese text)