Power generation by waste heat recovery

Th. Wiederkehr
〈**Holderbank**〉

Introduction

The paper at hand deals mainly with the economical aspects of power generation by waste heat recovery. Other applications of waste heat recovery, e.g. for heating purposes or process steam generation, are not subject of this discussion although we have gained experience within the "Holderbank" group of cement companies and found them to be very attractive, provided consumers of thermal energy or process steam are in the plant's vicinity.

The following aspects will be looked at in more detail during the presentation:

- Potential of modern kiln/cooler systems for power generation by waste heat recovery
- Schematic flowsheet of a waste heat recovery system
- Investment cost versus operating cost savings
- Possible impacts of waste heat recovery systems on cement plant process equipment
- Improving of kiln/cooler systems as alternative to waste heat recovery
- Outlook
- Concluding remarks

Quantitative figures given in this paper must be taken as a guide line only, the accurate values depend on the parameters of the specific plant under consideration.

Potential of modern kiln/cooler systems for power generation by waste heat recovery

Fig. 1. shows the heat balance of a 4–stage preheater kiln with grate cooler. It can be seen that 45% of the fuel brought into the system is fired to cover losses.

For power generation, the exhaust gas losses are of primary importance. Fig. 2 shows that up to 30 kwh/t of clinker can be generated by recovering these exhaust gas losses.

Schematic flowsheet of a waste heat recovery system for power generation

Fig. 3 shows schematically a system that can be applied for generating power by recovering the thermal energy contained in a gas stream. The water from the condenser is fed to the recovery boiler and preheated in the economizer. In the next higher part of the boiler, the water is evaporated and then the water vapor is superheated. The steam is expanded in a turbine driving the generator, condensed in the condensed in the condenser and then fed back into the circuit.

It goes without saying that the system must be tailored to each individual cement plant. Depending on the number, temperature level and performance of the various heat sources, the steamwater circuit may become somewhat

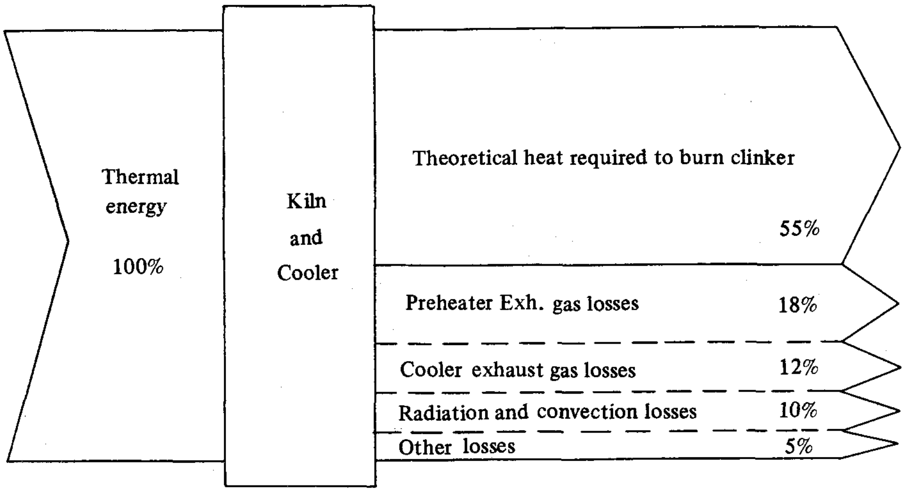


Fig. 1. Heat balance of a 4-stage preheater kiln with grate cooler

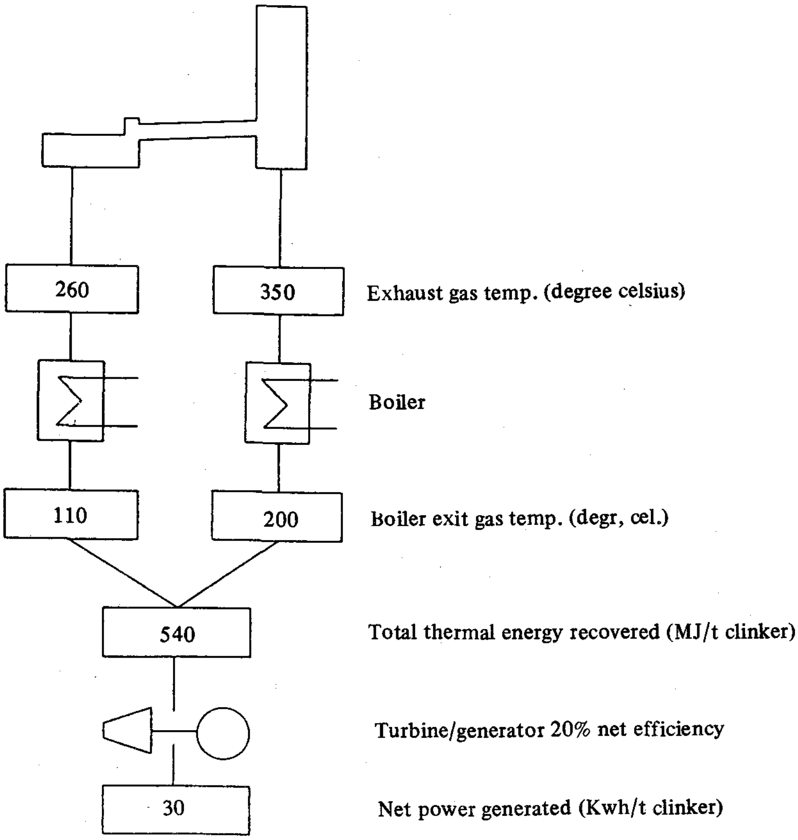


Fig. 2. Saving potential of a 4-stage preheater kiln with grate cooler. Heat consumption 3200 MJ/t

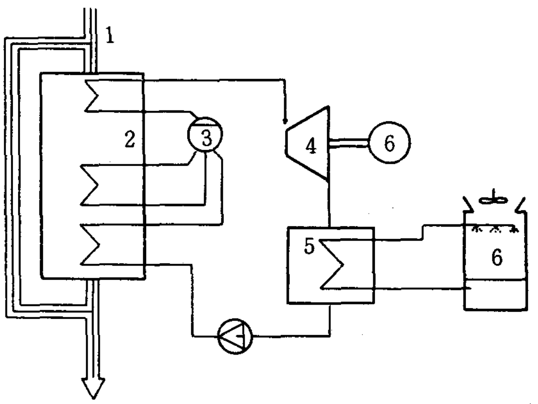
more complex (e.g. multipressure steam or steam/hot water system).

The cooling water system has to suit the availability of water, there is a variety of possible solutions to choose from.

Fig.–3 does not show auxiliary equipment for automatic cleaning of the boiler, the corrosion protection, the control, etc. These systems are of vital importance for the proper functioning of the power plant, but "Holderbank" has made the experience that they work very reliably when engineered properly and operated according to the supplier's manuals.

Investment cost versus operating cost savings

To get a very rough idea on the investment cost, one can assume a specific investment of 1000 US$ per kw installed performance of the power plant, i.e. a 5000 kw plant recovering heat from two sources would cost in the order of magnitude of 5 millions US$.



1) Exhaust gas duct
2) Waste heat recovery boiler
3) Steam drum
4) Turbine generator set
5) Condenser
6) Cooling tower
7) Feedwater pumps

Fig. 3. Schematic flowsheet of a waste heat recovery power plant

The specific investment will be pushed upwards by:

- Small units
- Decreasing performance and increasing number of heat sources
- Long distances between heat sources
- Complex layout of existing cement plant with limited availability of space.

To optimize the savings on the other hand, we engineer the heat recovery plant so that there is no extra staff required for operation and maintenance. We have proven within our own group of cement companies that this is possible.

The yearly maintenance cost will depend on the size and complexity of the power plant, but to get a first idea we calculate with a figure of 1.5% of the investment.

The raw material moisture content has an important influence on the amount of electric power generated. This shall be illustrated with diagram 1 to 3.

Quantitative figures may be valid for a 4,000 t/d 4-stage preheater kiln with grate cooler but again they must be considered as a guideline only.

The three diagrams apply to the same cement plant with a given course of the raw material moisture content. With rising moisture, the enengy requirement for raw material drying will increase. Therefore, the exhaust gases can not be cooled down that much in the boiler anymore and the output of the power plant will drop.

Diagram 1 shows a waste heat recovery plant that is matched to the minimum moisture content. It will therefore run on full load only during a short period of the year.

Diagram 2 shows a power plant with a nominal performance matching an average moisture content. The investment cost will be lower than for the power plant of digram 1, but on the other hand this plant will not be able to recover the

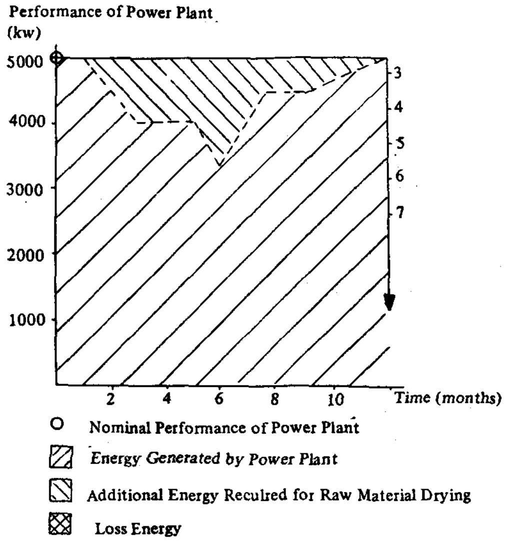


Diagram 1: Power plant matched to minimum moisture content

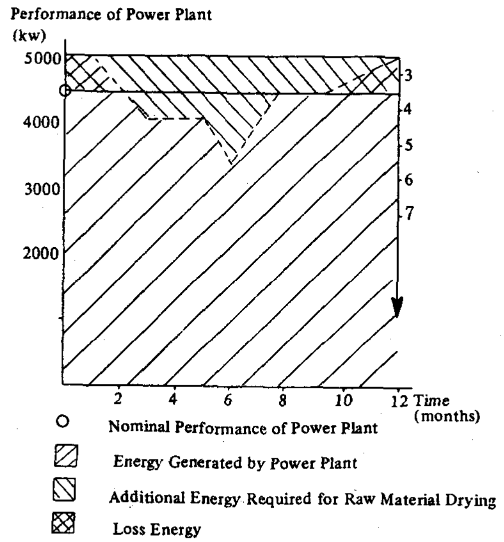


Diagram 2: Power plant matched to average moisture content

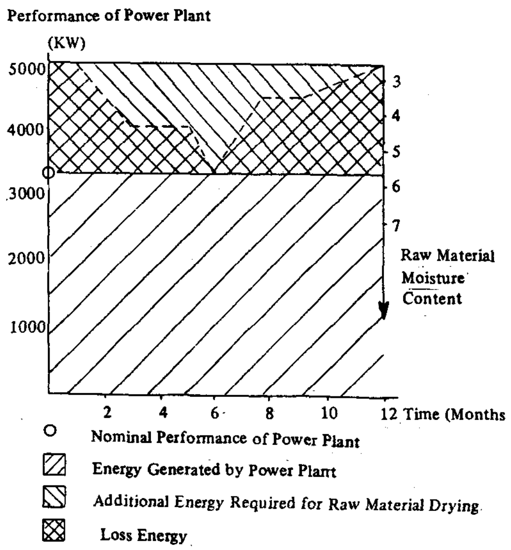


Diagram 3: Power plant matched to maximum moisture content

full amount of waste heat during the dry period.

In diagram 3, the power plant is matched to the maximum moisture content. The investment will be lowered even more, but a considerable amount of energy can not be recovered. Only economic considerations can reveal the optimum solution, i.e. the difference in investment cost has to be compared to the difference in operating cost savings.

When speaking about operating cost savings not only the power bill, which is often subdivided into demand, consumption and peak charges, but also the reliability of the utility net work has to be considered, since 30 kwh/t of clinker generated by a waste heat recovery plant often suffice to run the complete kiln feed, kiln,cooler and clinker transport equipment autonomously.

Possible impacts of the waste heat recovery system on the cement plant process equipment

The waste heat recovery plant must be designed in such a way that it does not adversly affect the cement plant equipment. To achieve this goal, the existing plant must be carefully investigated. In the following, two problem areas, namely the kiln exhaust gas handling and dedusting will be dealt with in some more detail.

The kiln exhaust gas fan

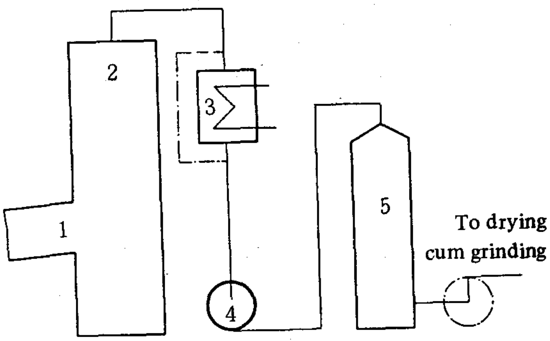
The formula for the performance of a fan, i.e.

$$\text{Performance} = \frac{\text{Gas volume x Pressure difference}}{\text{Efficiency}}$$

Indicates that the power consumption will rise due to the additional pressure drop over the recovery boiler. On the other hand, the cooling of the gases reduces it volume. As a rule of thumb, one can assume that cooling by 10°C will offset a pressure drop of 1 mbar. (Note, this is only valid for conditions encountered with a 4-stage preheater kiln). That is, at a pressure drop of 8 to 10 mbar, the power consumption of the fan will not increase if the gases are cooled by 80-100°C.

Fig. 4 shows the possible arrangement of the equipment in the exhaust gas stream. It must be noted that:

- In case the recovery plant is not run, the power consumption of the fan will rise if there is no boiler bypass provided.
- The characteristic of the gas duct system will change in any case and it must be checked



1) Kiln
2) Preheater
3) Waste heat recovery boiler
4) Exhaust gas fan
5) Cooling tower

Fig. 4. Possible arrangement of kiln exhaust gas fan

as well as size and performance of the existing electrostatic precipitator into account.

whether or not the fan is still suitable.

- Should the fan be installed after the conditioning tower, one can expect an additional power consumption of 1 kwh/t.

The electrostatic precipitator

The dry cooling of the exhaust gases could negatively affect the efficiency of the electrostatic precipitator. For the first assumptions, we would therefore limit the dry cooling in the kiln exhaust gas boiler to 200°C even with very dry raw material. At a later stage, the limit will have to be determined taking dust and gas properties

Improving of kiln/cooler system as alternative to waste heat recovery

The goal of this chapter is to show that:

1. Even with an ideal kiln system, there is a certain amount of waste heat available.
2. Under certain conditions, it is more economical to recover losses than to avoid them in the first place.

To show this, a little excursion into the process technology will be required.

Fig. 5 shows the boundry of a theoretical heat balance.

Not discussing futuristic clinkering processes, today's systems have two defined limits:

- 800°C exit gas temperature after the calcining stage.
- 1400°C clinker temperature at the cooler inlet.

The theoretical heat demand for the process between these limits is:

Dissociation of $CaCO_3$	2000 MJ/t-cli
Formation of clinker minerals	– 500 MJ/t-cli
Heat of melting	100 MJ/t-cli
Total theoretical demand	1600 MJ/t-cli

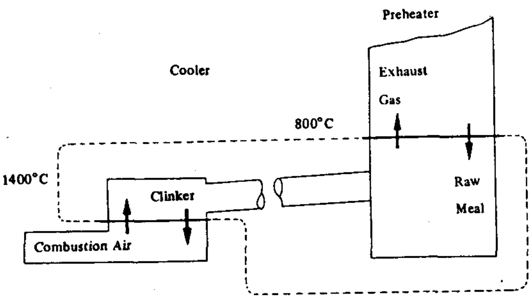


Fig. 5. Boundry for theoretical heat balance

which is 50% of a modern kiln system with a consumption of 3200 MJ/t-cli.

This is somewhat contradictory to Fig. 1 where the theoretical demand is given as 55% of the heat input. The difference is a result of the fact that the dehydration of clay minerals, a reaction requiring 180 MJ/t-cli, is usually added to the theoretical demand, whereas we maintain here, that it can be covered by heat exchange in the preheater.

Under the assumption that we have an ideal cooler (combustion air temperature equals clinker inlet temperature) and an ideal preheater (calcining stage exit temperature equals raw meal inlet temperature), we can now calculate the heat balance:

Cooler

Heat input by clinker	1500 MJ/t-cli
Heat required for preheating of combustion air	– 800 MJ/t-cli
Heat surplus	700 MJ/t-cli

Preheater

Sensible heat of exhaust gases	1000 MJ/t-cli
Heat required for preheating of raw meal	– 1370 MJ/t-cli
Heat required for dehydration of clay minerals	– 180 MJ/t-cli
Heat deficit	–550 MJ/t-cli

Overall balance

Heat surplus from cooler	700 MJ/t-cli
Heat deficit from preheater	–550 MJ/t-cli
Surplus of ideal system	150 MJ/t-cli

these considerations show that:

– Even the ideal kiln/cooler system with no losses at all will give a waste heat of 150 MJ/t-cli that could be converted at an efficiency of 20% into electric energy of 8 kwh/t-cli.

– With the ideal kiln system one has to cover the deficit a the preheater by bringing the surplus from the cooler to the preheater. or, the better the kiln, the more waste heat there is available at the cooler.

Our ultimate goal is to make a profit, respectively to save money. To do this, there are two ways:

1. Avoid the losses.
2. Recover the losses.

These two possibilities shall now be compared from the economic point of view.

The potential specific savings by avoiding the loss of thermal energy is

1600 MJ/t-cli x price/MJ of thermal energy.

On the other hand, the potential specific saving by recovering thermal energy and transform it into power is

(1600+150) MJ/t-cli x transformation efficiency x price/MJ of electrical energy.

Comparing the two potentials and neglecting the difference of 150 MJ, one finds that

> At a given investment, it is favourable to recover a certain amount of energy instead of avoiding its loss if the ratio
>
> $$\frac{\text{price for thermal energy}}{\text{price for electrical energy}}$$
>
> is smaller than the transformation efficiency.

In Korea for instance, according to our

information, this price ratio is 0.145 if coal is the source of thermal energy, i.e. a kwh of thermal energy costs only 14.5% of a kwh power.

In case bunker oil is the source of thermal energy, the ratio is 0.3.

The above said shall now be illustrated by an example.

Avoiding losses by building a 5-stage instead of a 4-stage preheater versus recovering the losses by building a bigger waste heat recovery plant

Operating cost saving:
5-stage versus 4-stage preheater:

Savings due to reduced heat consumption	
100 MJ/t cli x price/MJ	
= 100x1.8 Won	= 180 Won/t
Add. cost due to increased power consumption of exhaust gas fan	
0.3 kWh/t x price of power	
= 0.3 x 50 Won	= –15 Won/t
Total savings	165 Won/t

Recovering from 4-stage preheater versus recovering from 5-stage preheater:

Add. savings due to increased power generation	
65 MJ/t cli x transf. efficiency x price/MJ el. power	
65 x 0.2 x 50/3.6	= 180 Won/t
Difference of investment cost for a 4000 t/d plant:	
5-stage preheater versus 4-stage preheater	700 Millions Won
4400 kW versus 5000 kW recovery plant	500 Millions Won

I.e. the recovery approach offers higher specific savings at a lower investment!

Note: Although the heat consumption of the 5-stage preheater system drops by 100 MJ/t, the recovery plant looses only 65 MJ ofthermal energy. This is because an improved kiln system increases the available waste heat at the cooler.

Another possibility of taking advantage of low fuel prices compared to power prices would be to recover all waste heat from the preheater and run an auxiliary firing for raw material drying.

Generally speaking we must learn to widen our balance boundries, i.e. not to look only at a kiln, mill, cooler, etc., but at the plant as a whole.

Outlook

It is not our goal to predict the future trends of waste heat recovery systems but reference is made to a few arrangements which have been studied and partly realized within the "Holderbank" group of cement companies.

Cooler

Fig. 6 shows an schematic diagram of an exhaust gas free clinker cooler. Instead of getting rid of surplus heat by dedusting hot exhaust gases and venting them to the atmoshpere, here the exhaust gases are cooled in a recovery boiler

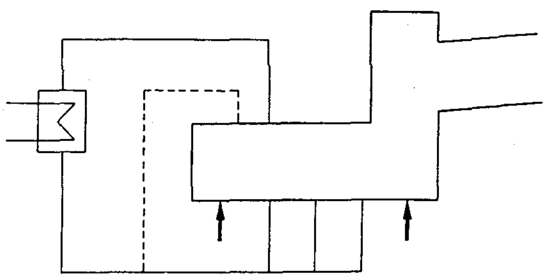


Fig. 6 Exhaust gas free cooler system

and reintroduced into the undergrate compartments. We have this system running in one of our plants, although we do not transform the waste heat into power.

It is obvious that the investment for the recovery equipment is at least partly offset by the absence of the dedusting equipment. In an ency, one could build a second circulating loop (dotted line) without intermediary cooling. Probably, the air of this circuit would not be mixed with the one from the boiler, but reintroduced separately.

Preheater

One mean of increasing the amount of available waste heat is to avoid radiation losses. In this field as well, we have gained some experience.

Another possibility e.g. in case of a conversion to a precalciner system in order to increase the capacity of an existing preheater kiln, would be to branch off a part of the exhaust gases after the precalciner. Like this, the existing preheater could remain and a very hot source of exhaust gases would be available for the recovery system. This solution of course would result in an increased heat consumption of the kiln but, depending on the price ratio between thermal and electrical energy, the system may be feasible.

attempt to increase the transformation effici-

Concluding remarks

When speaking about waste heat recovery systems, the following points should be kept in mind:

- The systems must be tailormade to suit the technical and economical environment of your individual plant.
- A waste heat recovery system can be introduced at any time, but preferably in the course of a conversion, rehabilitation or extension, rehabilitation or extension project or when a new plant is built.
- The influence of the waste heat recovery system on the process equipment of the cement plant has to be studied carefully.
- Do not jump to conclusions, neither to positive nor negative ones.

"Holderbank" has gained experience with waste heat recovery systems which form a part of a strategy of saving energy in cement plants developed under the umbrella of "Total Energy Consumption and Cost Analysis" (TECCA).

"Holderbank" with its broad experience in cement technology and engineering is at your services during engineering, manufacturing, erection, commissioning and operation of tailormade systems that reduce the operating cost and increase the capacity of your plants.