Low Grade Heat Recovery

Hilel Legmann and David Citrin, ORMAT International, Inc., USA, report on the importance of recovering unused heat from the grate cooler and the development of the Organic Rankine Cycle (ORC) clinker cooler heat recovery system.

Introduction

Even for an optimised cement burning process, significant heat losses, mainly caused by the heat of the waste gases, still occur. The heat balance of a kiln plant reveals that preheater waste gases and cooler exhaust air account for more than 30% of that heat loss (Table 1).

Power generation from unused heat sources

One approach to overcome this economically unsatisfactory situation is to use the waste heat for the generation of electrical power. In the past few years some cement plant operators have installed steam waste-heat boilers in the waste-heat piping of their plants and have utilised the process heat with or without additional external burning to operate a steam turbine-generator set. Reports on these systems have been published.

However, on examination, the conventional steam technology presents certain drawbacks with respect to its practicability and applicability to the cement production process:

- The use of the relatively low temperature grate-cooler exhaust air, available at continuously varying temperatures ranging from 165˚C to 304˚C (see Figure 1), involves difficulties with respect to stable steam turbine operation. To overcome this drawback, the exhaust air temperatures have been raised, in some cases beyond the level required for clinker burning, through additional fuel gas firing. This has increased the fuel consumption in the plant to unacceptable levels.
- As an alternative approach, it has been suggested to interconnect the steam boilers of grate-cooler and preheater, whereby the grate-cooler boiler acts as economiser and tertiary evaporator for the boiler installed for the cyclone preheater. However, few such systems have been installed in the industry. Such systems, which include the use of preheater gases, have limitations as:
    - Many plants would utilise part of the preheater gas heat stream for raw mill drying.
    - The high dust loading in preheater gases results in high cost and complex steam boilers with few qualified manufacturers.
    - Even if the technical difficulties in manufacturing such boilers could be overcome, such systems in most countries would be economical only for very large-scale cement plants (more than approximately 2.5 million tpa).
- Furthermore, cement plants should consider factors such as the instability and low efficiency of the relatively small steam turbines at partial-load operation, caused by the fluctuation of the grate-cooler air, the necessity to have a dedicated steam plant operator on a shift basis thus increasing the personnel costs of the plant, and the necessity to shut down the complete system in case of failures.

All the above points constitute the background for this newly developed concept as described in this paper.

The heat recovery system is based on the thermodynamic Organic Rankine Cycle (ORC) air-cooled power module, the ORMAT® Energy Converter (OEC), which generates electricity from the heat recovered from the clinker cooler. In order to recover the waste heat from the clinker cooler air, a conventional tube heat exchanger was installed after the ESP. The heat

Table 1. Heat consumption for cement clinker burning

	Heat quantity referred to clinker	
	kJ/kg	%
Theoretical heat requirement	1760	54
Waste gas heat (preheater)	755	23
Exhaust air heat (grate cooler)	355	11
Wall heat loss (preheater, kiln, cooler)	335	10
Heat discharged in clinker	65	2
Total	3270*	100

**See footnote at the end of the article.*

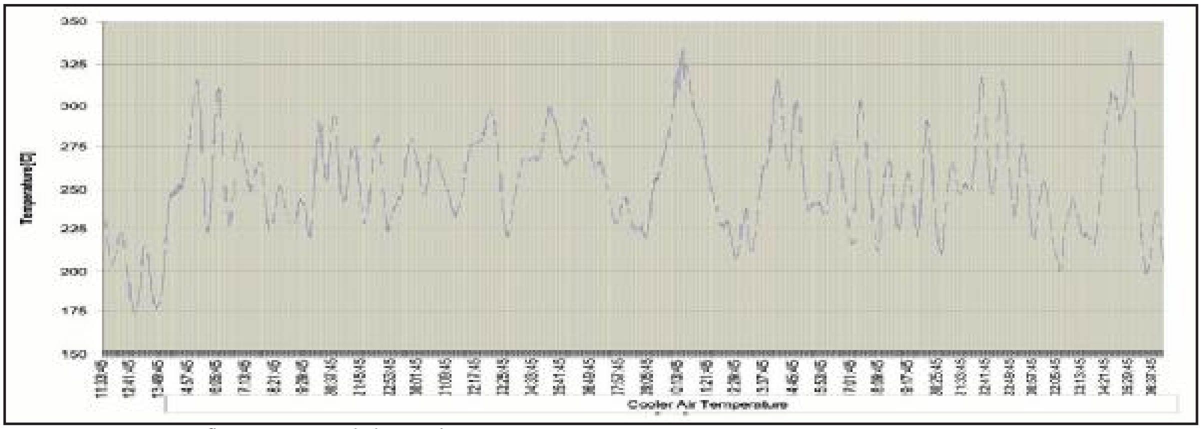

Figure 1. Temperature fluctuation in a clinker cooler.

is transferred to the OEC by means of a thermal oil flow circulating in a closed loop system. The OEC's heat exchangers utilise the hot thermal oil to evaporate a hydrocarbon motive fluid (N-pentane, in this specific case). The pentane vapours are expanded in the turbine, condensed in the air-cooled condenser and then returned in a closed loop to the vapouriser by means of a high-pressure pump (see Figure 3).

This concept was implemented in 1999 for the first time in the cement industry at the Lengfurt plant of HeidelbergCement AG in Germany. This 100 year old facility is a modern, well-operated and maintained plant having a production capacity of over 1 million tpa of clinker.

ORC technology

The fundamental principle of the ORC is the use of a low boiling point organic fluid as the cycle's working fluid, which exchanges heat and is vapourised by the primary heat source. The organic vapour then expands into the turbine, condenses and is recycled.

For low and moderate enthalpy heat, ORC technology offers many advantages over the conventional steam Rankine cycle, primarily due to higher efficiency in the recovery of the sensible heat stream and also because of the simplicity of the turbine, the control system and the balance of the plant.

Due to the ratio of latent to sensible heat in the cycle, the use of an organic cycle allows for greater heat recovery than is possible with a steam cycle. Table 2 is a comparison of the key parameters affecting power output from a 160°C temperature hot water heat source. Note that for this case the ORC cycle is capable of producing 30% more power than the steam cycle.

The difference in ratios of sensible to latent heat mentioned before can be seen from the TS diagrams (Figure 2).

From the TS diagram it can also be seen that, when the organic vapour expands in the turbine, it tends to superheat or become dryer, unlike steam, which becomes wetter during the expansion process. Therefore, superheating of the organic vapour prior to delivery to the turbine is not required.

The distinguishing features of an Organic Rankine Cycle compared to a conventional steam Rankine cycle can be summarised as follows:

- Greater efficiency for lower temperature resources, as described above.
- Smaller size turbines and piping:
  Hydrocarbons, such as pentane, have a lower specific volume than steam. This results in smaller turbines, particularly reducing the height of the turbine's last stage blades, smaller diameter exhaust piping and smaller diameter tubes in the air-cooled condenser. The relative pressure and density of steam vs. pentane can be seen in Table 3.
- Moisture-free turbine expansion:
  Unlike steam, pentane remains dry during the expansion from high to low pressure; a consequence of the hydrocarbon's thermodynamic properties. This eliminates the possibility of moisture formation, and the likelihood of erosion damage when high-speed droplets collide with the turbine's buckets and nozzles. Thus, the ORC can accommodate part load operation and large transients more effectively than steam turbines, without requiring a superheater.

Table 2. Comparison of organic and steam cycles for a 160°C hot water heat source

	Steam	Organic
% Of pre-heat	9.3%	37%
Optimum exit temp.	94°C	72°C
Heat input	72%	100%
Thermal efficiency	14.5%	14%
Power	75%	100%

Table 3. The relative pressure and densities of steam vs. pentane.

T (°C)	Steam pressure (bara)	Steam density (kg/m³)	Pentane pressure (bara)	Pentane density (kg/m³)
50	0.12	0.08	1.60	4.57
100	1.01	0.60	5.89	16.49
150	4.76	2.55	16.0	47.77

- Suitable for air-cooled applications:
  In many applications, there may be a preference for the use of air-cooling due to the lack of availability of water. The ORC plant's air-cooled condenser is much smaller and less expensive than an air-cooled condenser designed for steam duty. This is a direct consequence of the order of magnitude difference in volumes between hydrocarbons (pentane) and steam as in Table 3.
- High vapour turbine efficiency at low speed:
  Due to the low acoustic velocity of hydrocarbon fluids, compared to steam, favourable aerodynamic matching is achieved at low blade speed. This yields high turbine efficiency at 50 or 60 Hz (1500 or 1800 rpm) without a gearbox.
- Condensing near atmospheric pressure:
  Hydrocarbons condense at higher pressure than steam. By operating at condensing pressures near, but above, atmospheric, the risk of leakage of air into the system is significantly reduced and the need for vacuum maintenance is minimised.
- Not susceptible to freezing:
  Hydrocarbons freeze at temperatures below -73°C. This allows the condenser to reject its heat at a lower temperature than water-based systems and, in doing so, increases output in cold weather. This feature also eliminates the requirement to implement procedures and controls to prevent freeze-up within the condenser.

The Thermal Oil – OEC System

At the initial design stage, it had been intended to recover approximately both 9.5 MWt heat from the clinker cooler air and 10.7 MWt from the preheater gases (total 20.2 MWt heat) by circulating a single thermo oil flow in a closed loop through both heat sources and feeding it to one air cooled 3.5 MWe OEC unit. However, further to some budget restrictions, the final design ignored the heat from the preheater gases and recovered 8.2 MWt from the clinker cooler air, feeding the thermo oil into a 1.5 MWe OEC unit.

Figure 3 outlines the basic operating principle of the thermal oil OEC system for the generation of electrical power from waste heat in a cement plant:

- The heat contained in the wasted clinker cooler is transferred to a thermal oil flow circulating in a low-pressure loop. The thermal oil heat content is transferred to the OEC motive fluid in the vaporiser and preheater.
- The power generation process itself (preheating, vaporising, expanding, condensing and pumping of the liquid phase organic motive fluid) takes place in the OEC unit in a fully automatic operating mode.

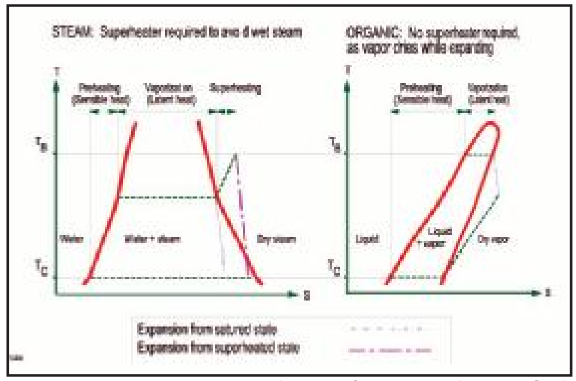

Figure 2. Temperature - entropy diagrams for water and organic fluid.

Lengfurt – design criteria

The criteria governing the design process of this OEC heat recovery application (see Table 4) were as follows:

- Matching the design criteria to the specific characteristics of the heat source and to the environment. Thermal oil (Mobiltherm 594) and the working organic fluid (N-pentane) were chosen to enable the system to work efficiently and stably within the given temperature and pressure parameters.
- A series of bypasses installed in the hot air flow, thermal oil and pentane loops to be installed to ensure no negative interference with the host plant's production operations.
- Low speed turbine (3000 rpm) directly connected to the asynchronous generator, and computerised controls including automatic synchronisation and preprogrammed safe shutdown procedures were determined as the key elements for simple operation and maintenance.

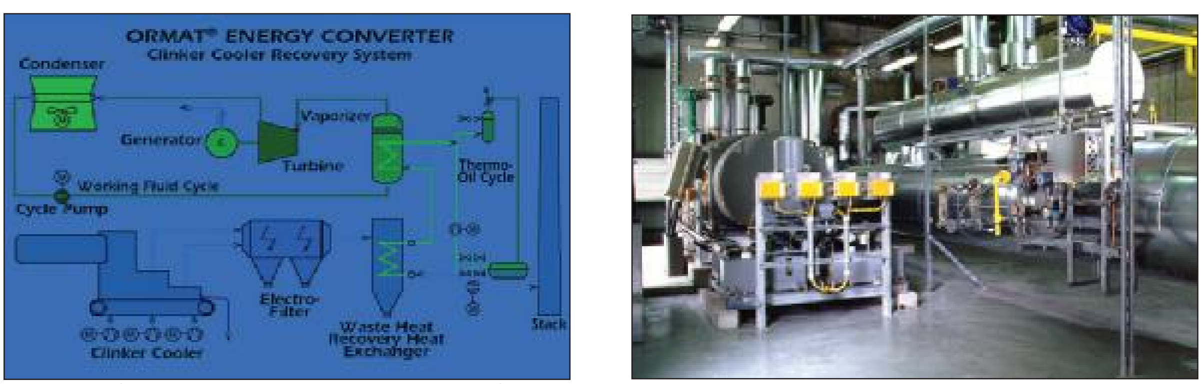

Figure 3. (Left and right) The basic operating principle of the thermal oil OEC system.

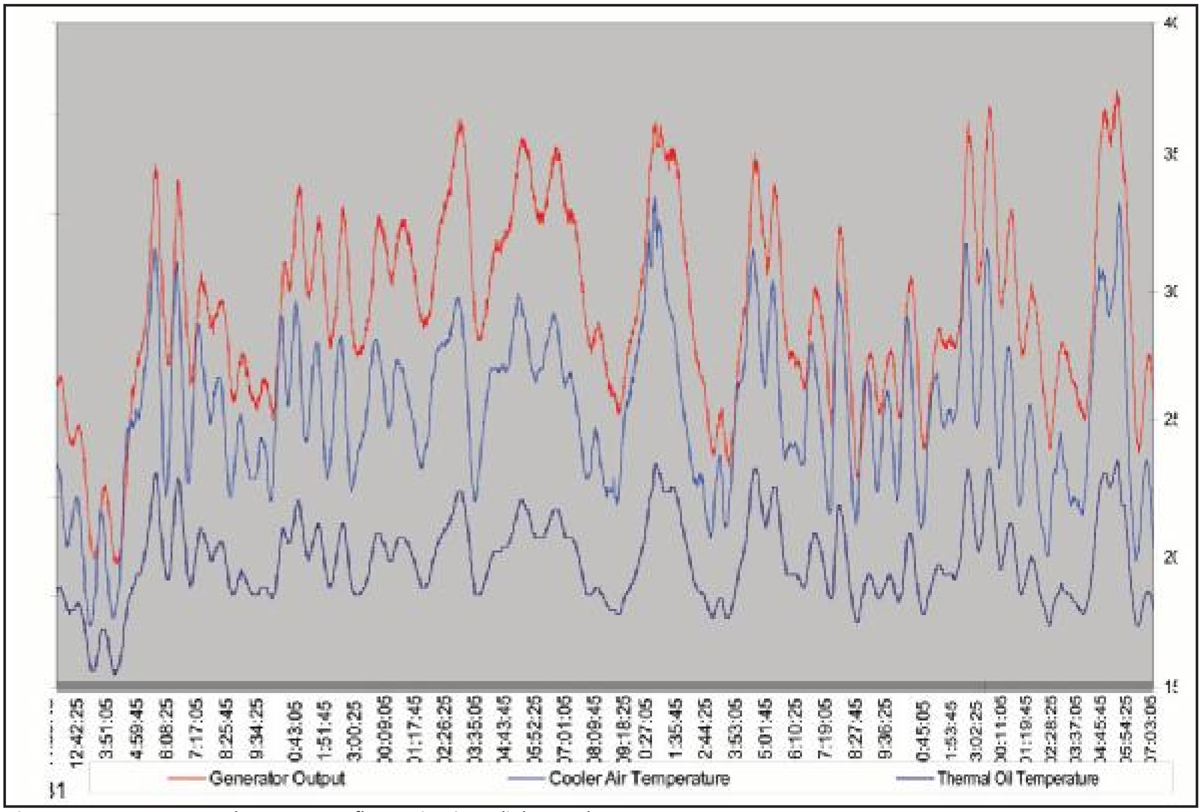

Figure 4. Temperature and OEC output fluctuation in a clinker cooler.

- Proven technologies were the key elements to ensure rapid and low cost installation and no cost overruns.
- Fully automatic and unattended operation.
- Field proven components were used to ensure maximum system availability.
- The organic power cycle was selected due to the flexibility required to cope with the continuously changing heat source conditions in both flows and temperatures. The grate cooler air temperature fluctuates between 340˚C and 180˚C, which was determined would cause the thermo oil temperature to fluctuate between 230˚C and 120˚C. In coping with such fluctuations, the power unit would be generating between 1500 and 400 kW (Figure 4).

Operating experience

In summarising the initial five years of operation, the following should be highlighted:

- The OEC unit has proved that its operation is extremely flexible and can accommodate a wide range of ‘off design conditions’. As a result of fluctuating operating conditions as described above, power output fluctuations between 400 to 1400 kW occur automatically within minutes. The ability of the system to cope and operate in such off-design ranges without any damage, is unique to the OEC. No other power cycle has proven similar abilities, suggesting that this may be the best technology currently available for this application.
- Since its initial operation, the power module has achieved average annual availabilities of over 98%, proving that the ORC can operate in the process industries with the same high plant availability that has been proven in the geothermal industry where the system is used to deliver high quality base load power.
- The operation of the system is fully automatic, and does not interfere with the clinker production, nor does it cause any additional work for or disturbance to the kiln operators.
- The operation and maintenance of the system is simple and has been easily handled by the plant’s own mechanical and electrical staff. The long-term average maintenance cost was established on a 7-10 % lower budget than initially anticipated.
- During its five years of commercial operation, the system has generated electricity without one major incident or malfunction, without any major overhaul of components and with practically no loss of the organic working fluid.
- With the award of the Bavarian Energy Prize 2002, the project was recognised for its innovative contribution towards energy generation and the environment.

Conclusion

The ORC power cycle based clinker cooler air heat recovery system at Lengfurt has successfully met

Table 4. Technical data		
Plant data		
Plant production		1 million tpa
Heat recovered from the grate cooler		8.2 MW_t
Grate cooler	- air flow	150 000 Nm^3/hr
	- temperature in/out	275 / 125°C
Thermal oil cycle		
	flow	85 tph
	temperature in/out	230 / 85°C
OEC data		
Rated generation capacity		1.5 MW
Vaporiser type		Tube and shell type
Materials		TEMA Class 'C' BEM
Tubes and shell		Carbon steel
Cooling side data		
Cooling media		Ambient air
OEC turbine		
Turbine manufacturer		ORMAT
Turbine type		Specially designed impulse type
Rotation shaft speed		3015 rpm
Generator		
Rated output		1.5 MW
Rated voltage		690 Volt / 50 Hz / 3-phase
Type		Induction
Rotation speed at full load		3015 rpm
Number of poles		2
Motive fluid		
Working fluid type		Hydrocarbon (N-pentane)
Electricity generation		1300 kW continuous operation, varying according to inlet conditions (grate cooler air temperature variation).
Plant's power savings		The generated power is equivalent to about 12% of the plant's own electricity demand.
Mode of operation		Unattended, fully automatic, remote monitoring
Additional effects of the projects		Reduces pollution of CO_2 by 7600 tpa
Equipment delivery time		25 Weeks
Erection time		3 Weeks
System availability - average over first 5 years		Above 98%
Recorded yearly maintenance cost over the first 5 years of operation (average)		US$6.800 (equivalent to less than 0.001$/kWh)

HeidelbergCement's design criteria and the objectives of this pilot commercial scale project. It has proven the capability of the ORC in converting into electric power the low temperature heat from the clinker cooler exhaust and in coping automatically and seamlessly with wide fluctuations in heat source temperatures and flows.

The ORC based ORMAT® Energy Converter (OEC) at Lengfurt has demonstrated an average availability of over 98% over approximately five years of continuous unattended operation, with low operation and maintenance costs and without causing problems for the plant personnel.

*Note: Data reflects the energy consumption as per 1987. The value for 1998 was 2905 kJ/kg and the specific value for HeidelbergCement was 2800 kJ/kg. In principle, direct utilisation of these waste heat sources, e.g. for drying of raw material, coal or intergrading matter, yields maximum efficiency and may be utilised. However, there are numerous plants where this utilisation is either not possible or not required, so that the unused heat is indeed lost. The economic order of magnitude of such losses in a typical kiln line of 2000 tpd capacity with a 4-stage cyclone preheater and grate cooler can be assessed as follows: Assuming a preheater waste-gas temperature of 350°C and grate cooler exhaust-air temperature of 277°C, approximately 1100 kJ/kg of clinker of unused heat is lost. If the source of energy is firing coal with a net calorific value of 23 000 kJ/kg, the annual loss to be attributed to unused process heat is approximately US $1.0 - $1.6 million. The challenge posed by such an immense loss of energy should be tackled. Electricity generation is proposed here as the preferred solution.