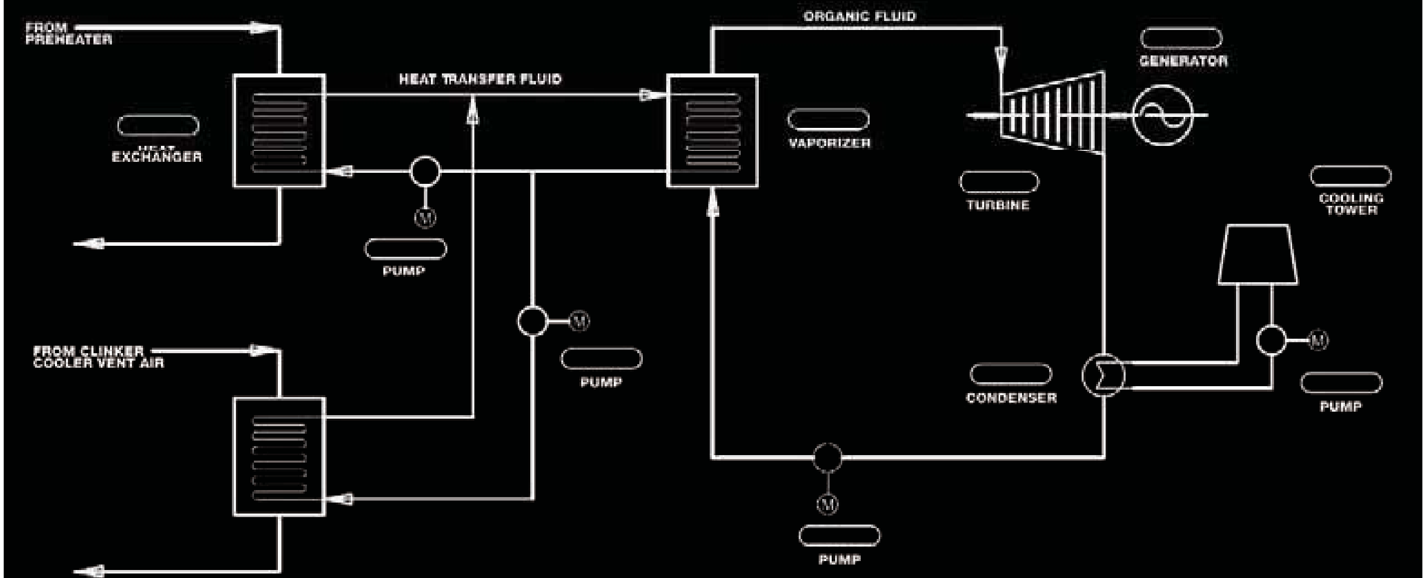

WASTE HEAT RECOVERY SYSTEMS

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Lately, there has been a significant increase in interest for waste heat recovery power generation (WHRPG) systems in the cement industry. This interest is generated from companies' sustainability policies, companies searching for projects with acceptable returns on investment, legislation changes, and the need to produce electric power onsite.

The preheater exit gases and the clinker cooler vent air are two sources of waste heat that are available and commonly used for waste heat recovery (WHR). The amount of waste heat available for recovery depends on the kiln system design and production, and amount of heat required for drying in the raw mill system, solid fuel system and cement mill system.

WHRPG systems

WHRPG systems used for cement kiln systems operate based on the Rankine Cycle. These WHRPG systems consist of heat exchangers or heat recovery steam generators (HRSG), turbines, electric generators, condensers, and a working fluid cooling system.

Three primary types of WHR systems are available, with the working fluid being the differentiating factor.

- The most common system used in cement plant applications uses water as its working fluid. This system is commonly referred to as the "conventional Rankine Cycle system".
- The second type of system uses an organic fluid, such as N-pentane, as its working fluid. This system is commonly referred to as the "Organic Rankine Cycle (ORC) system".

- The third type of system uses a mixture of ammonia and water. This system is commonly referred to as the “Kalina Cycle® system”.

Conventional Rankine system

The conventional Rankine Cycle system uses water as its working fluid. Figures 1 and 2 show the temperature-entropy charts of two different system configurations. Figures 3 and 4 show the corresponding flow diagrams.

The conventional Rankine Cycle consists of the following process steps:

1. Process 1 shown in Figure 1 (from point 1 to 2): the water exiting the condenser is pumped to the HRSG where it is preheated.
2. Process 2 shown in Figure 1 (from point 2 to 3): the water is then converted to steam (boiled) in the HRSG.
3. Process 3 shown in Figure 1 (from point 3 to 4): the steam is superheated (heated to a temperature above its saturation temperature at the actual pressure conditions).
4. Process 4 shown in Figure 1 (from point 4 to 6): the superheated steam expands in the turbine, generating power. This line reflects the turbine at its operating efficiency. The expansion decreases the steam temperature and pressure. The line from point 4 to 5 would be for a 100% efficient turbine.
5. Process 5 shown in Figure 1 (from point 6 to 1): the steam/water exiting the turbine is condensed to liquid form in the condenser.

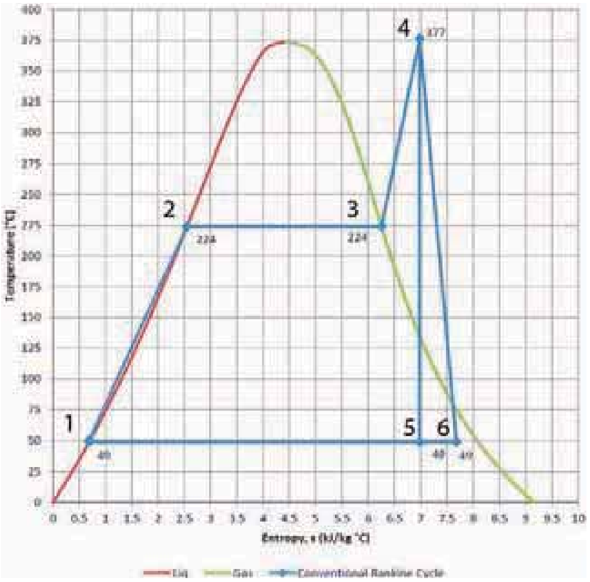

Figure 1. T-S chart, conventional Rankine Cycle, one pressure level.

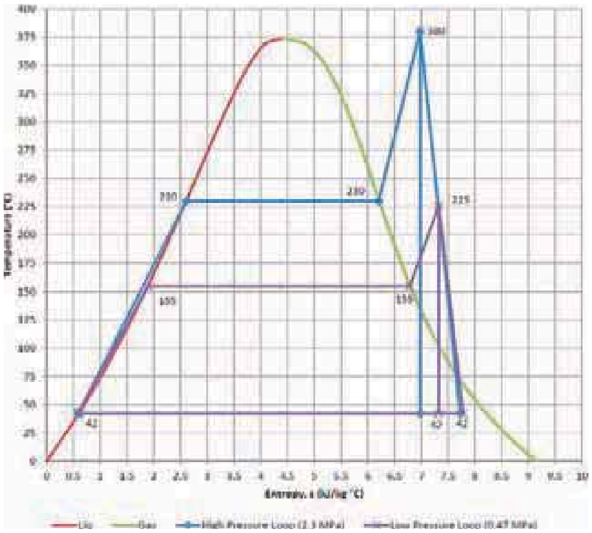

Figure 2. T-S chart, conventional Rankine Cycle, two pressure levels.

The conventional Rankine system has several potential drawbacks. The main potential drawback is high turbine blade erosion rate.

Water droplets impinging on the blades at high speed cause high erosion on the turbine last stage blades. The recommended steam quality exiting the turbine is 90 – 95% steam to minimise erosion damage (note that the 5 – 10% would be in the form of water droplets). The steam quality at the turbine exit is affected by the following factors:

- Turbine steam inlet conditions.
- Turbine efficiency.
- Condensing conditions at the exit of the turbine.

Typically, when designing a WHR system the objective would be to maximise the power generated. To accomplish this requires the minimisation of the condensing temperature and pressure, and maximal efficiency of the turbine selected. This decreases the steam quality, thus increasing the amount of droplets at the turbine exit. The turbine steam inlet conditions can be designed to maintain appropriate conditions. This will maintain the recommended steam quality exiting the turbine, provided the waste heat source is at a sufficiently high temperature. For reference, a turbine inlet pressure of 2.3 MPa requires the steam temperature to be in the range of 300 to 385 °C. At lower steam pressures, the required steam temperature range would be lower.

In cement plant applications where the preheater exit gases are near 300 °C, the WHR system designer may elect to pass the steam from the preheater to a super heater located in the clinker cooler vent air to achieve the required steam temperature. Figures 2 and 4 show this design. However, the air temperature variation from the clinker cooler is substantially higher than from the preheater. This variation may result in steam temperatures at times lower than the required temperature to ensure the recommended steam quality. When this happens the erosion rate increases, resulting in increased maintenance requirements or possibly the need to shut down the system.

Organic Rankine System

The ORC system uses an organic fluid as its working fluid. Figure 5 shows the temperature-entropy chart for a typical ORC system, while Figure 6 shows a schematic of the ORC for heat recovery from the preheater gases and clinker cooler air.

Note that the ORC systems are designed with two heat transfer stages. The first stage transfers heat from the waste gases to a heat transfer fluid (thermal oil or water). The second stage transfers heat from the thermal oil or water to the organic fluid.

The ORC has several advantages over the conventional Rankine system. They include the following:

- The organic fluid properties result in the working fluid remaining dry throughout the turbine, thereby avoiding any erosion problems. In Figure 5, the line between points 4 and 5 shows this process.
- The organic fluid properties permit some of the heat in the working fluid exiting the turbine to be transferred to the working fluid exiting the pump (condenser exit); thereby increasing the overall cycle efficiency. In Figure 5, the line between points 5 and 6 shows the portion of the condensing process with the potentially recoverable heat.
- If the heat is transferred to the working fluid exiting the pump, then the required amount of heat to dissipate from the condenser would be lower than the amount required otherwise. This would reduce the size of the condenser system. It would also reduce the amount of water consumed in the cooling tower, or the amount of air used in the air heat exchanger.
- The organic fluid properties permit the WHR system to recover heat from gases that are at a lower temperature than what is possible with a conventional Rankine system.
- ORC systems are designed with the condensing pressure near but above atmospheric pressure. N-pentane, one of the organic fluids used in ORC systems, has a condensation temperature of 36 ˚C at one atmosphere pressure. This reduces the risk of air leakage into the ORC system and eliminates the requirement for a de-aerator as in the case of the conventional Rankine cycle system.
- The organic fluid is not susceptible to freezing. Hydrocarbons freeze at temperatures below -73 ˚C. N-pentane has a freezing temperature of -129.8 ˚C.
- The turbine would have fewer stages compared to the steam turbine.

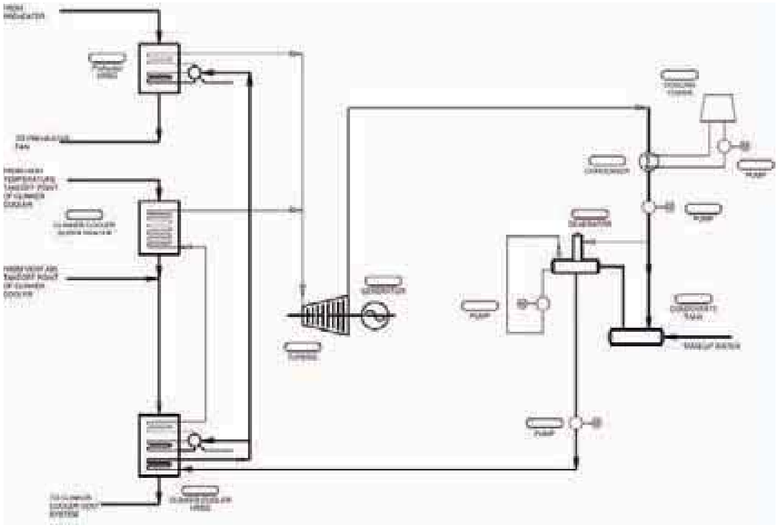

Figure 3. Flow diagram, conventional Rankine Cycle, one pressure level.

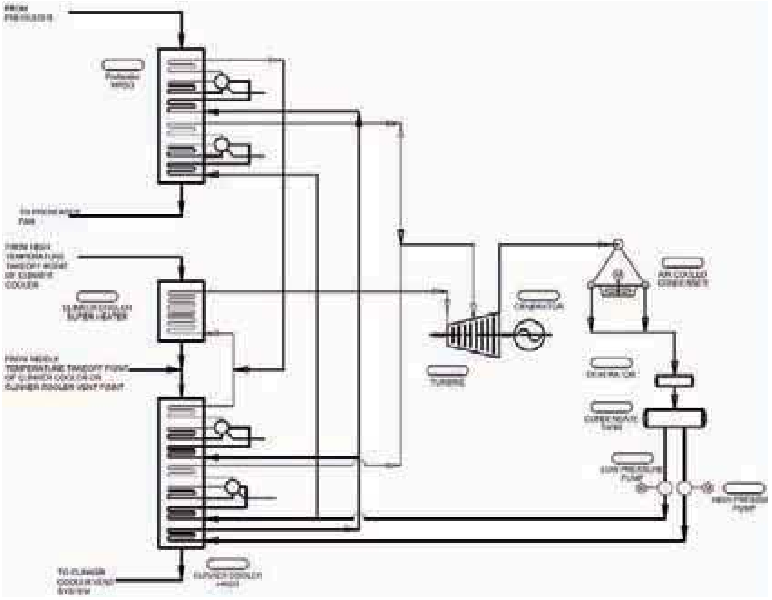

Figure 4. Flow diagram, conventional Rankine Cycle, two pressure levels.

- The piping from the heat exchangers to the turbine would be smaller in diameter than those required for a steam system.
- ORC systems can withstand larger temperature variations of the preheater and clinker cooler gases used for waste heat recovery.
- Depending on the application, the ORC system may have a lower specific cost than the conventional Rankine system.
- Typically, the ORC system has lower maintenance costs than the conventional Rankine Cycle system.

The ORC system also has its disadvantages, including:

- It does not generate as much power as the conventional Rankine system.
- Depending on the application, the ORC system may have a higher specific cost.
- Heat transfer fluids and organic fluids normally used in these systems are combustible. If used, the system would require measures for fire protection, and replacement after a certain amount of operating time. It is also an environmental concern if there are any leaks.

Kalina Cycle®

The Kalina Cycle® is a thermal cycle for energy conversion that uses a mixture of ammonia and water as its working fluid. Figure 7 shows a schematic of the Kalina Cycle® WHRPG system. For more information on this technology, please refer to presentations at the IEEE conference in 2005 and 2007.[1, 2]

The Kalina Cycle® WHRPG system has several advantages over the conventional Rankine Cycle and the ORC system. They include the following:

- The system can be used in lower temperature applications than the conventional Rankine Cycle system.
- The working fluid is not flammable.
- The system requires only one heat transfer stage.

System installations

WHRPG in the cement industry is dominated primarily by the conventional steam and water Rankine cycle systems. One of the system suppliers, for example, has 106 installations listed between 1980 and 2011.[3]

To date, the ORC system has had limited installations in the cement industry. Ormat, one of the ORC system suppliers, has two installations, of which one is at the HeidelbergCement plant at Lengfurt.[4] At this plant, waste heat is recovered from the clinker cooler vent air. The second reference plant is located at AP Cement, Tadipatri, Andhra Pradesh, India.[5] ABB is another supplier of the ORC system. At the time of writing, the author is not aware of any ABB systems installed and operating in a cement plant. However, Holcim has recently contracted with ABB to install an ORC system at its Untervaz, Switzerland plant.[6] The author is not aware of any other ORC system suppliers currently supplying systems to the cement industry, although there are numerous ORC installations in other industries. Ormat has over 240 ORC units ranging from 300 – 8000 kW and over 45 geothermal and waste heat power plants.[4]

Global Geothermal Limited and Recurrent Engineering LLC, both subsidiaries of Wasabi Energy, supply the Kalina Cycle® systems. To date, a full scale system is not operating in the cement industry. However, Wasabi Energy recently announced that it has secured a contract to build a Kalina Cycle® power plant at D.G. Khan Cement Company's Knairpur cement plant in Pakistan.[7] The Kalina Cycle® system has been installed in other industries, such as steel making, oil refinery and municipal incineration.

Summary

This article has highlighted some of the advantages and disadvantages of each system. Other considerations that need to be addressed for a successful installation include optimum system sizing, the optimum system configuration, the expected variation in waste heat source, the heat exchanger or HRSG design, the condenser system selection and the water treatment system. Additional items for consideration include whether to install a system to recover waste heat from more than one kiln system at a time and preferences of equipment suppliers. The selection of the optimum solution requires a detailed evaluation of many variables.

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Figure 5. Organic Rankine Cycle, temperature-entropy chart.

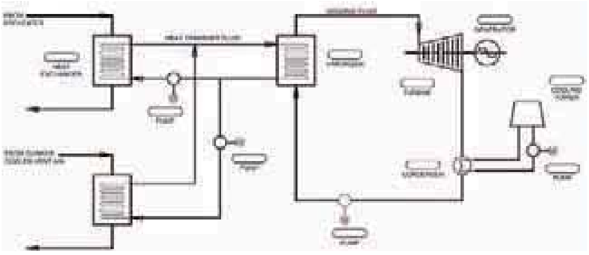

Figure 6. Organic Rankine Cycle WHRPG.

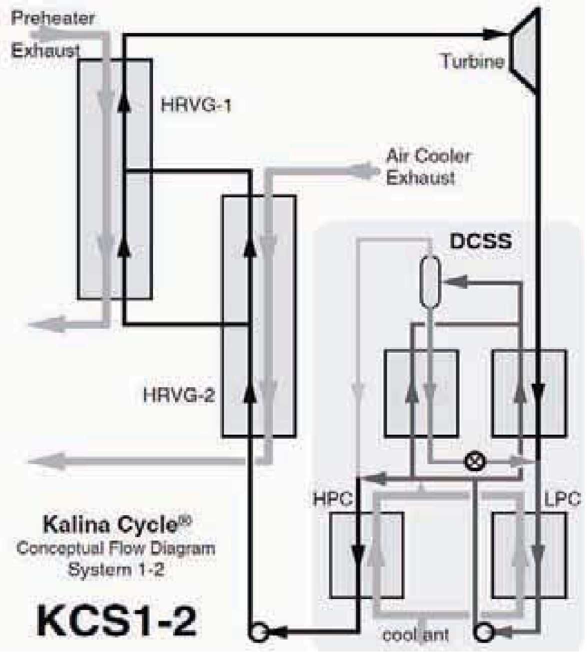

Figure 7. Kalina Cycle® WHRPG (source: Mirolli, 2005).