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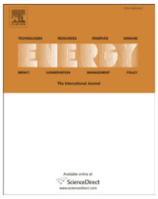

Organic Rankine cycle saves energy and reduces gas emissions for cement production

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A B S T R A C T

We investigated ORCs (organic Rankine cycles) integrated with typical China cement production line. The dry air at the kiln cooler outlet with the temperature of 220 °C was the waste heat. The fluids of hexane, isohexane, R601, R123 and R245fa were selected for ORCs based on the critical temperature criterion. The developed ORC verified the thermodynamics analysis. The NPV (net present value) and PBP (payback period) methods were applied to evaluate the economic performance. The LCA (life cycle assessment) was applied to evaluate the environment impacts. ORCs could generate 67,85,540–81,21,650 kWh electricity per year, equivalent to save 2035–2436 tons standard coal and reduce 7743–9268 tons CO_2 emission, for a 4000 t/d cement production line. ORCs reduced gas emissions of CO_2 by 0.62–0.74%, SO_2 by 3.83–4.59% and NO_x by 1.36–1.63%. The PBP (payback period) was 2.74–3.42 years. The ORCs had the reduction ratios of EIL (environment impact load) by 1.49–1.83%, GWP (global warming potential) by 0.74–0.92%, AP (acidification potential) by 2.34–2.84%, EP (eutrophication potential) by 0.96–1.22% and HTP (human toxicity potential) by 2.38–2.89%. The ORC with R601 as the fluid had the best economic performance and significant gas emission reductions. ORCs had good economic performance and reduce the gas emissions.

1. Introduction

The cement industry is a basic raw material industry to influence a country's economy and people's life. It has attained a considerable scale in China. The annual output of cement was about 2414 million tons, accounting for about 60% of the world's cement output in 2012 [1]. There are large quantities of low grade waste heat during the cement production process. As the second largest waste heat resource among the seven industry sectors of steel, cement, glass, synthetic ammonia, caustic soda, calcium carbide, sulphuric acid, the waste heat in the cement industry was equivalent to 93 million tons standard coal in China [2]. The waste heat driven power generation technologies have evolved three generations in the cement industry. The available power generation technologies use relatively high grade waste heat. The water-vapor Rankine cycle was used, with the vapor temperature higher than 370 °C. The power generation system is complicated and the investment cost is high [3].

Recently, ORC (organic Rankine cycle) has been investigated widely. ORC can be driven by low temperature hest source with the temperature of lower than 300 °C. ORC is favorable compared with conventional water-vapor Rankine cycle. The heat source of ORC can be solar energy, biomass energy, biogas energy, geothermal and industrial waste heat etc. ORC can also be driven by the waste heat in the cement industry to generate power or electricity. At present, the ORC investigations have been focused on the selection of working fluids, the cycle performance, the economy analysis and the environmental impact analysis.

The ORC performance is strongly dependent on the organic fluids. Lakew & Bolland [4] investigated ORCs using the fluids of R134a, R123, R227ea, R245fa, R290 and n-pentane. The results showed that the ORC with the fluid of R227ea yielded the maximum power output when the heat source temperatures were in the range of 80–160 °C. Meanwhile, R245fa produced highest power output with the heat source temperature in the range of 160–200 °C. Hung et al. [5] selected organic fluids by setting the system thermal efficiency as the target parameter. The turbine inlet pressure and temperature, turbine exit quality, condenser exit temperature, overall irreversibility and system efficiency were considered. The studies showed that wet organic fluids produced higher thermal efficiencies than dry fluids. A higher turbine inlet temperature and a lower condensation temperature could generate an economic feasible and environment friendly energy conversion system. Tchanche et al. [6] compared ORC efficiencies, volume flow rate,

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mass flow rate, pressure ratio, toxicity, flammability, ODP (ozone depletion potential) and GWP (global warming potential) using twenty organic fluids. It was found that R134 was more suitable for small scale solar energy utilizations. The fluids of R152a, R600a and R290 were attractive in the ORC thermal efficiencies. But attention should be paid to the flammability and safety issues of these fluids.

The frequently used ORC evaluation parameters were the thermal efficiency, heat recovery efficiency, exergy efficiency, net power or work, volume flow rate, expansion ratio in turbines, APR (heat exchanger area per unit power output), etc. Dai et al. [7] examined effects of various thermodynamic parameters on the ORC performance. They set the exergy efficiency as the objective parameter. ORCs were investigated using different working fluids under similar heat source conditions. It was found that ORCs were much better in their performances compared with water-vapor Rankine cycles. ORC with R236ea as the working fluid had maximum exergy efficiency. Roy et al. [8] investigated ORCs by setting the system thermal efficiency, turbine work output, irreversibility rate and second law efficiency as the objective parameters. The fluids of R123 and R134a were considered. They concluded that R123 had better ORC performance than R134 for low temperature waste heat utilizations. Wei et al. [9] optimized ORC using HFC-245fa as the working fluid. The increases in the work output and thermal efficiencies could raise the waste heat utilization degree. The running parameters of ORCs shall consider the environment impact. Roy et al. [10] maximized the work output and thermal efficiencies to optimize the turbine inlet pressure. The fluids of R12, R124, R134a and R123 were used, with R123 having the maximum work output and thermal efficiencies. Zhang et al. [11] used the thermal efficiency, exergy efficiency, recovery efficiency, APR and LEC (levelized energy cost) as the objective parameters to quantify the subcritical and transcritical ORCs for geothermal energy utilizations.

Recently, some researchers investigated the ORC environment impact and economic feasibility. Liu et al. [12] applied the LCA (life cycle assessment) to evaluate the EI (environment impact) for waste heat driven ORCs. It was found that the GWP (global warming potential) is the most serious EI followed by the HTP (human toxicity potential). Walsh & Thornley [13] evaluated the environment impact and economic feasibility for the metallurgical coke production process by introducing ORC to recover the waste heat in the process. It was found that introducing ORC to the coke generation process could reduce 1–3% of CO_2 emission, which was equivalent to decrease 10,000 tons of CO_2 emission annually. The discounted payback period was about three to six years. Tchanche et al. [14] investigated the economic feasibility of ORC for waste heat recovery. For a 2 kWe ORC, the specific installation cost was 5775 €/kW with a LEC (levelized electricity cost) of 13.27 c€/kWh. Alternatively, a 50 kWe ORC had the specific installation cost of about 3034 €/kW with the LEC of 7 c€/kWh. Kosmadakis et al. [15] reported the economic evaluation of two-stage solar driven ORC for reverse osmosis desalination. The specific fresh water cost was 6.85 €/m^3, approaching the value of the Photovoltaic-Reverse Osmosis system.

Here we investigate ORCs for waste heat recovery in the cement industry. Various organic fluids with proper thermodynamic parameters were considered. The technology-economy indicators of the NPV (net present value) and the PBP (payback period) were applied to evaluate the economic feasibility. Using the LCA data for China energy production, the ORC introduced to the cement production process was evaluated with one ton cement production as the functional unit.

2. The cement production process

Calcination is the core technique during the cement production process. The cement industry has experienced following stages in the history: the shaft kiln, dry hollow kiln, wet process kiln, lepol kiln, preheater kiln and outside pre-decomposition calciner. The NSP (New Suspension Preheater) cement production technology (including the suspension preheating and pre-decomposition technologies) becomes the main technology in the world due to its outstanding advantages for cement production. The NSP cement production process mainly include raw material mining and homogenizing, energy-saving grinding, high efficiency and low pressure drop pre-heater and calciner, grate cooler and high performance thermal insulation material.

The NSP cement production technique consisted of three main stages: raw material preparation, clinker sintering, cement production and storage. Fig. 1 shows the flow chart of the cement production process.

The raw material preparation stage treats the limestone and auxiliary raw material to satisfy the material sintering requirement, physically. The calcareous raw material, clayey raw material and ferro-controlling raw material are crushed and dried. Then they are sent to the material storage room where they are mixed according to specific ratios. The mixture is further milled to form high quality raw material powder, which is to be further homogenized.

The clinker sintering is one of the major processes for the NSP cement production, consisting of the outside-kiln preheating and decomposition, inside-kiln sintering, clinker cooling and exhausts gas processes. The raw material powder is elevated to the preheater where it is heated. The raw material receives heat from the hot gas stream in multi-pre-heaters to reach a high temperature. Then it enters the decomposition furnace to make the powders decomposition. The decomposed material is calcined to reach the partial melting state in the rotary kiln to form the high temperature clinker, which is then crushed and cooled in the kilneye.

The final cement production process is described as follows. The gypsum and slag are mixed with the clinker. The formed mixture is grinded into fine powders by the cement grinding machine. Then the cement is ready to be dispatched. The cement milling system and packaging system are involved in the final production process [16].

Usually, the NSP cement production line has the thermal utilization efficiency of about 50–60%. Table 1 shows the heat consumption percentage of various components or processes for a 4000 t/d cement production line of China. Except the heat consumed by the clinker, the pre-heater and the exhaust gas at the cooler outlet dissipated about 33% of the total heat. The outlet temperature of the kiln tail pre-heater is normally 330 °C. The exhaust gas at the kiln cooler outlet is 220 °C. Different cement production quantities have different waste heat quantities. This paper discussed the waste heat driven ORCs. The waste heat resource comes from the heat carrier fluid at the kiln cooler outlet. The main parameters can be found in Ref. [17]. The heat carrier fluid is hot air having its temperature of 220 °C and mass flow rate of 43.02–82.73 kg/s.

3. The ORC working principle

Fig. 2 shows a basic ORC configuration, mainly consisting of an expander, a condenser, a fluid circulating pump and an evaporator. Fig. 3 shows the T-s diagram. The thermodynamic cycle includes an expansion process (1–2), a condensation process (2–4), a pumping process (4–5) and an evaporation process (5–1). The following assumptions are made to simplify the analysis:

- The steady flow and heat transfer state within the ORC;
- The saturated liquid state at the condenser outlet;
- The saturated vapor state at the evaporator outlet;
- No heat loss from the ORC component to the environment;
- No pressure drops with fluid flowing in pipelines.