In the EU27 the industrial sector represents nearly a quarter of final energy consumption and one-fifth of GHG emissions. About 75 per cent of this energy is used in thermal processes (kilns, furnaces, reactors, boilers, dryers, etc) and a significant part is ultimately discharged as waste heat.

Industries such as the cement sector can reduce these losses by improving equipment efficiency or by installing heat recovery technologies (eg, exchangers, heat pumps) to make use of the waste heat inside the plant or exchange it with surrounding factories or residential communities. In the absence of any such re-use, conversion into electricity becomes an attractive solution, but one that still needs development.

**Low temperatures: a challenging target**

Thermodynamic cycles, especially the organic Rankine cycle (ORC), make it possible to recover low-temperature waste heat to generate electricity. Producing power from waste heat typically involves using the heat to create mechanical energy to drive an electric generator. Today the development of ORC technology is considerably advanced and there now exist many providers of commercial solutions for heat recovery applications. However, there is little or no industrial experience on heat recovery at temperatures below 250°C, due to the low
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Cement mill flue gas recovery

Cement mill flue gas is usually discharged in the air via a stack. The gas consists of humid air (dewpoint –60°C) with temperature in the range of 90-120°C and low dust content. To make use of this waste heat, a 50kWe prototype was designed and tested at Armines’ laboratory and then installed at Cemex’s cement plant in Beckum, Germany. An indirect contact heat recovery system (fin-and-tube heat exchanger) was used to obtain heat exchange between the source and the ORC working fluid (see Figure 1).

In total, the ORC system installed at the Cemex site worked for more than 516h, mostly in automatic mode, producing a maximum gross electric power of 42kWe, in accordance with theoretical calculations. Significant heat losses were experienced at the turbine and the heat exchanger – the latter due to insulation missing in some areas to permit access and control.

Raw mill flue gas recovery

Raw mill flue gas originates from the kiln combustion process and contains a significant amount of acidic emission (SO2, NOx), together with an important level of humidity (dewpoint –62°C). This gas has temperatures in the range of 95-120°C. Commonly, cooling of gas with these characteristics is restricted to a minimum safe temperature to prevent water vapour condensation and acid formation. However, cooling temperatures down to below the flue gas dewpoint improves the overall efficiency of the recovery system because the latent heat of water vapour can be recovered. The aim of LOVE was to exploit this potential, minimising the risks of corrosion. For this purpose, water was used as a heat transfer fluid in an intermediate loop and its pH was controlled by injecting a NaOH solution (30 per cent by volume). A hybrid heat recovery system was designed to maximise the heat recovery. A direct contact heat exchanger (packed column unit) was used to recover the latent heat, combined with an indirect contact heat exchanger (fin-and-tube heat exchanger) designed to recover the sensible heat at temperatures above the flue gas dewpoint (see Figure 2). A 100kWe prototype was designed and tested at Armines’ laboratory, and then installed at Holcim’s cement plant in Höver, Germany.

The combination of direct and indirect heat exchangers proved to be highly sensitive to variations in gas inlet conditions and very strong fluctuations were observed. In addition, while the fin-and-tube heat exchanger performed according to its design, the packed column unit did not reach its nominal performance level. This was because process gas conditions did not fulfil specifications that required the inlet gas dewpoint temperature be higher than the packed column unit inlet water temperature. To decrease the packed column unit inlet water temperature, the ORC evaporation temperature would have to be lowered, but this would have had a negative influence of ORC cycle efficiency.

Despite the high availability of raw mill flue gas (24h/d) the ORC prototype system control was not developed enough to ensure running of the system without an operator present. As a result, the prototype was tested during the daytime only. In total, the ORC system installed at the Holcim site ran for more than 55h and reached a performance close to its expected design level. Its maximum gross power output reached
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80kWe compared to the 100kWe design output level. The limited working hours were mainly due to significant corrosion problems encountered by the hybrid heat extraction unit which eventually resulted in the shutdown of the system. A detailed investigation showed that corrosion was generated by construction and installation issues, i.e., large vibrations on the heat extraction unit and inadequate thickness of the heat exchanger tubes (<0.8mm thickness copper tubes). These aspects could easily be improved in a new installation.

Key lessons learned

The testing of the demonstrators proved the technical feasibility of power generation by ORC using low-temperature waste heat in real industrial environments. The harsh operating conditions that the prototypes were exposed to helped highlight the advantages and limits of the technologies and the materials used. In particular, for the raw mill heat extraction system, the results showed accelerated corrosion problems in the presence of vibrations and structural inhomogeneity of the heat extraction system (i.e., variation of HEX tubes thickness). The experiments also revealed that such systems must be designed to adapt automatically to changing process conditions over a significant range. The size of the recovery heat exchanger proved to be a critical factor at low temperature, as well as the adaptation to the production process.

The achieved gross ORC system efficiency (i.e., from ORC fluid input to turbine output) was around six per cent. The overall system efficiency (i.e., from gas input to turbine output) was approximately three per cent. These efficiencies are low but in accordance with expectations considering the thermodynamic limitations (Carnot efficiency) of low-temperature power cycles and the partial optimisation of auxiliary components. In particular, the cooling tower, which for cost saving was the same for the two prototypes, proved to require a specific adaptation to the system. The availability of a cold source would significantly improve the overall system performance. Still, a scaled-up industrial application is not yet economically viable under actual market conditions. Cost effectiveness can be reached only if the technologies become standard.

Further investigations must aim for power conversion technologies with a higher yield, optimisation of all auxiliary components and the standardisation of flexible components. Integration with other waste heat sources at higher temperatures could also introduce advantages and should be studied on a case-by-case basis. Continuing collaboration between industry and academia can help enhance technical development and achieve large-scale industrial implementation of waste heat energy recovery systems.
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