Transforming waste heat into electricity

Steam expansion engine makes efficient and flexible use of low-temperature heat with ORC technology

Anyone generating electricity or operating high-temperature industrial processes produces waste heat. This waste heat is often not utilised, since its economic use does not seem viable. Small plants using the Organic Rankine Cycle (ORC) promise help here: they make the waste heat usable in the form of electricity, improve the cost-effectiveness and reduce CO₂ emissions. Researchers from Saarland have developed an engine that uses low-temperature heat to generate electricity very efficiently for a large range of uses.

Engines convert around one third of their fuel into usable energy. Two thirds are transformed into waste heat. Usually, this heat energy vanishes unused through the exhaust or the chimney. Researchers from Saarbrücken want to change that. Since 2004, a spin-off company from Saarland University of Applied Sciences (HTW) has been working on this aspect on behalf of the automotive industry. Major German manufacturers want to feed the heat from car exhaust gases through mobile steam circuits in order to reduce the fuel consumption by around a tenth. In 2007, graduate engineer Michael Schmidt came up with the idea of using the technology in industry to increase electricity yields. “Many components of our steam expansion engine are mass produced and can be easily modified to utilise heat flows from small power plants.” Since 2009 a demonstration plant has been connected to a coalmine gas engine at the nearby Fenne power plant. In the meantime 12 members of staff are now working in Saarbrücken on steam circuits for engines and are testing new components for at least one thousand operating hours in the demonstration system.
**More electricity with fewer components**

The standard technology for utilising waste heat is provided by ORC turbines. Their intermediate thermal oil circuit means that they often use complicated system technology. Fraunhofer researchers in Oberhausen have now developed turbines that dispense with thermal oil. However, turbines have a narrow optimal operating point, which with lower loads in partial load operation considerably reduces their efficiency.

With the ORC process using a steam expansion engine, on the other hand, the high temperature difference in the heat exchanger (HE) leads to a greater overall efficiency, which enables the electricity production ($P_{el}$) to be doubled for the same heat provision (Fig. 1). The high efficiency is due to the high enthalpy gradient in the engine. That means that a considerable amount of the energy available in the waste heat is transformed into usable energy. Interesting in energy terms is the further utilisation of the waste heat in the two ORC modules: the cooling water from the condenser is also available as usable heat for drying and heating. This has enabled the demonstration plant for the steam expansion engine in Fenne in Saarland to utilise more than 90% of the heat energy used.

In contrast to turbines, here it has been shown that the same engine can be used for various output levels between 100 and 200 kW. This enables variable balancing of the different pressure and temperature levels. Schmidt refers to the experience gained in Fenne: “When the cooling water temperature increases in summer, we can adjust the expansion ratio and thus the output of the gas piston engine. A turbine would have to be idle.”

**Demonstration plant as development hub**

The power plant site at Fenne is home to one of the world’s largest engine systems for generating electricity from coalmine gas, which consists mainly of methane (CH$_4$). It is released during underground hard coal mining and flows out of disused mines. The demonstration plant, which is connected to one of fourteen 3-MW coalmine gas engines, began operation at the beginning of 2009. A maximum heat output of 1.3 MW is derived from the exhaust gas system (marked red in Fig. 2). The exhaust flow has a temperature of more than 400 °C. In a 7 m-high evaporator, the heat is largely transferred to ethanol as the working fluid. It flows in the green-coloured circuit and reaches temperatures of up to 300 °C.

“On hearing the word ethanol, it is its combustibility that comes to mind,” says Michael Schmidt. “But that applies to many organic working fluids. In Fenne, we have invested a quarter of our development work in control and regulation technology that enables secure operation without supervision in accordance with recognised industrial standards.” Here the highest safety requirements apply, since the operation takes place in closed rooms and the power plant is subject to mining law. The cooling water flows from the condenser (blue) at a maximum temperature of 90 °C. It is used for further purposes such as heating, drying and cooling (after adsorption). In Fenne, the cooling water heats the condensate for other power plant blocks.

**Field test started**

“We have developed a highly efficient ORC process for waste heat flows between 200 and 500 °C, which in Germany is suitable for up to 500 industrial enterprises and around 1,000 larger CHP plants with capacities exceeding 1.2 MW,” says Schmidt in reference to the field test that is now beginning with four different plant types. “In contrast to turbines, our engine is not dependent on the rotational speed, which means that the fluctuating heat flows are also highly suitable for partial-load uses. Instead of electricity, we can also sell mechanical shaft power that enables, for example, compressed air to be produced from exhaust heat.”

The field test will show how the overall system copes after many thousands of operating hours. In addition to a biogas plant near Bremen, the waste heat from melting tanks in the glass industry and from casting kilns in the metal and chemical industries shall be used in test plants. “All this is being conducted with proven industry partners to ensure that we achieve market maturity in 2013 as planned,” emphasises Schmidt. The six ORC modules with their steam expansion engines shall then be transferred to a metal foundry in Bad Kitzingen, where a project funded by the German Federal Environment Agency has just begun. By launching the first large-scale use of the innovative plant combination for utilising exhaust heat, the company wants to reduce its CO$_2$ emissions by more than 8,000 tonnes a year. In addition to electricity, the use of steam expansion engines instead of conventional turbines and the use of ethanol instead of silicon oil as the ORC working fluid will also enable compressed air to be produced. For the field test, the developers are installing the ORC module in a stand-
ardised container. Because the heat exchanger is placed outside the container, the system can quickly adapt to the respective heat source. Even with the very first “Kirchwalsede” field test plant, which is a biogas plant near Bremen, only those components are included in the container that will be standard in every new ORC system. These comprise the machine bed with the steam expansion engine along with the generator, oil cooling system, pump station, technical ventilation and switch cabinets, which contain the proprietary developed control and regulation unit. Within the container, the engine, pump and switch cabinets are located in separate rooms. This enables all parts of the ORC module to be accessed separately. The engine is positioned so that it can be removed from the front end without any great effort and without having to dismantle the generator by using either a mobile crane located in the container or a standard forklift truck. This makes it easier to maintain and enables it to be completely replaced much more quickly.

In order to save on space and also foundations for further components such as the heat exchanger and emergency cooling systems, the Saarland researchers have developed a separate roof structure that will be placed on the container with a suitable frame. The container has been structurally redesigned, strengthened in accordance with the load distributions and tested. This reduces the overall floor space for the plant to the size of a 30-foot container (9 m length).

**Organic Rankine Cycle (ORC)**

The ORC system is named after Scottish physicist William Rankine (1820 - 1872), who is considered one of the founding fathers of thermodynamics. The ORC system is similar to the steam cycle used in coal-fired power plants, except in this case water is replaced as the working fluid with an organic working fluid that evaporates at lower temperatures and thus possesses more efficient thermodynamic properties than water. In order to achieve the greatest possible efficiency, the temperature of the heat source determines whether alcohol, (silicon) oil or a refrigerant is used. The working fluid also makes it possible to apply an effective steam pressure on the expansion engine or turbine – whose rotating shaft is used to generate electricity – with waste heat at temperatures below 600 °C. ORC technology can use waste heat from both industrial processes and renewable energy sources. Potential users include large-scale bakeries, glass and paper factories, steel and cement works, CHP plants that use biomass or biogas, coalmine gas or landfill gas, geothermal energy and solar energy (solar thermal).

**Further research requirements**

The Saarbrücken researchers have developed new ORC working fluids as part of a joint project conducted with a specialist chemical company. On a new testing rig, three to five different fluids are being tested that function either with low waste heat temperatures under 150 °C or with temperatures above 450 °C. The new working fluids should be durable and stable, without being environmentally harmful, toxic or combustible. “Here there is no competition with turbines. All ORC techniIcians are interested in this,” says Schmidt. “That also applies to the development of improved heat exchangers. Here I am seeing too few genuine innovations.” Together with a manufacturer of heat exchangers, he is looking for a direct evaporator for dust-laden flue gases with temperatures above 600 °C. At the same time, acid in the flue gas should be prevented at less than 130 °C in order to improve the corrosion protection, whereby new cleaning and filtering systems for particle-laden flue gases should provide help.

**Marketing underway**

Sufficient operating experience has now been gained to be able to determine the economic feasibility of the ORC steam expansion engine. Connected to the ovens of a foundry, two 200-kW engines can generate 2.8 million kWh of electricity a year based on 3 MW of waste heat. This will make it possible for the ORC plant to pay for itself in less than 5 years and, if the residual heat is used for heating, in less than 3 years (calculation based on 6.5 ct/kWh including levies and fees). An attractive feature for industrial enterprises is the fact that the plant can be operated without on-site personnel by means of remote monitoring. The ORC plant from Saarbrücken synchronises itself fully automatically with the electricity grid. This is particularly important with discontinuous waste heat flows if the new ORC technology is to fully benefit from its advantages in practice.
The market for wasted energy

It seems ridiculous in light of industry complaints about excessive energy prices: the market value of the unused waste heat in Germany exceeds 25 billion euros a year. Researchers have calculated that the final energy consumption for industrial process heat, which amounted to 1,600 petajoules (PJ) in 2007, was equivalent to around two thirds of the final energy requirements of Germany’s industry in the same year. The waste heat is created almost everywhere, whereby the sources are diverse: machines that release heat to their surroundings, waste water from washing, dyeing and cooling processes as well as exhaust gases from ovens and engines. For temperatures greater than 140 °C, it is estimated that in economic terms German industry has a waste heat potential of 316 PJ per year or 12% of the final industrial energy consumption and a further 160 PJ per year for temperatures between 60 and 140 °C, whereby this does not even take into account the potential provided by small and medium-sized companies or new CHP plants. With domestic energy generation amounting to around 4,000 PJ each year, probably up to around 1,000 PJ or almost a quarter of the energy generated in Germany is wasted as exhaust heat.

Since the thermal utilisation of waste heat is limited in many places, a particularly attractive aspect is the ability to use the waste heat to generate electricity, which can be more diversely used. Particularly the efficiency of engines used in CHP plants operated with (bio)gas can be considerably improved by utilising their exhaust heat. The developers of new ORC modules with turbines or steam expansion engines promise to increase the electrical power yield in addition to the engine output by up to 14 per cent. The researchers therefore want to realise the vision of decentralised engine combined cycle power plants with overall electrical efficiencies of almost 50 per cent. These “ECC” power plants enable decentralised electricity generation to approach the efficiency of modern large-scale power plants using technology that can be immediately implemented.

There would also be much to be gained in climate policy terms if the otherwise “cooled away” waste heat were to be transformed into electricity. The utilisation of a typical industrial waste heat source of 2 MW can prevent more than 4,000 tonnes of CO₂ each year. In order to systematically develop such waste heat sources, public registers are being set up in increasingly more federal states in Germany. In Saxony a “waste heat atlas” is being created and in Saarland a “heat sink register”.

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